Physics at the EIC

based on drawing by Enki Bilal

Thomas Ullrich

Midsummer School in QCD 2024
24 June - 6 July 2024
Saariselkä, Finland

Brookhaven National Laboratory

The Electron-Ion Collider does not exist

The Electron-Ion Collider does not exist

yet

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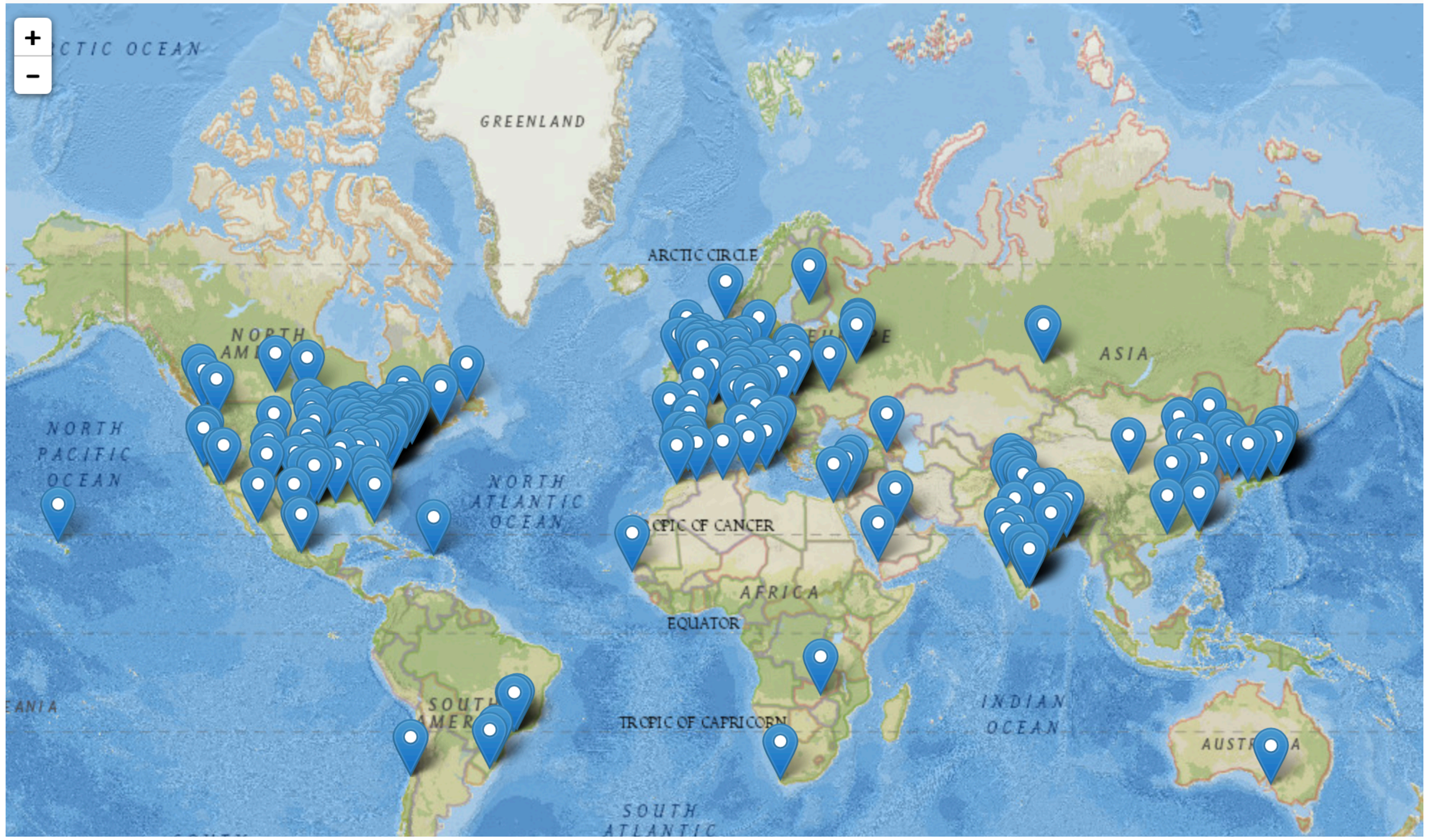


Over 1500 people from 294 institutions and 40 countries are working hard to make it happen within the next decade.

I am one of them.

About Me

- Senior scientist at BNL, EIC Group Leader, Prof. (adj) at Yale
- Origins
  - Ph.D University of Heidelberg
  - Heavy-Ion Physics: EM probes, chiral symmetry (NA45/CERES@SPS), and Heavy Flavor (STAR@RHIC)
  - EIC: high parton densities, CGC, diffraction, detector technologies
  - APS Fellow, former LHCC, NSAC member, …
- EIC Involvement
  - Active since 2006 - Town Meeting, NSAC Long Range Plans
  - Co-author of EIC White Paper (e+A section)
  - Coordinator of generic EIC detector R&D program (2014-2021)
  - L3 manager of project R&D program
  - Founding Member of EIC User Group
  - Coordination/Organization of Yellow Report
  - PID CC Working Group Convener
  - Council vice chair
- Software
  - SARTRE (diff. event generator), xyscan (tool to extract data points from plots), some cool games too

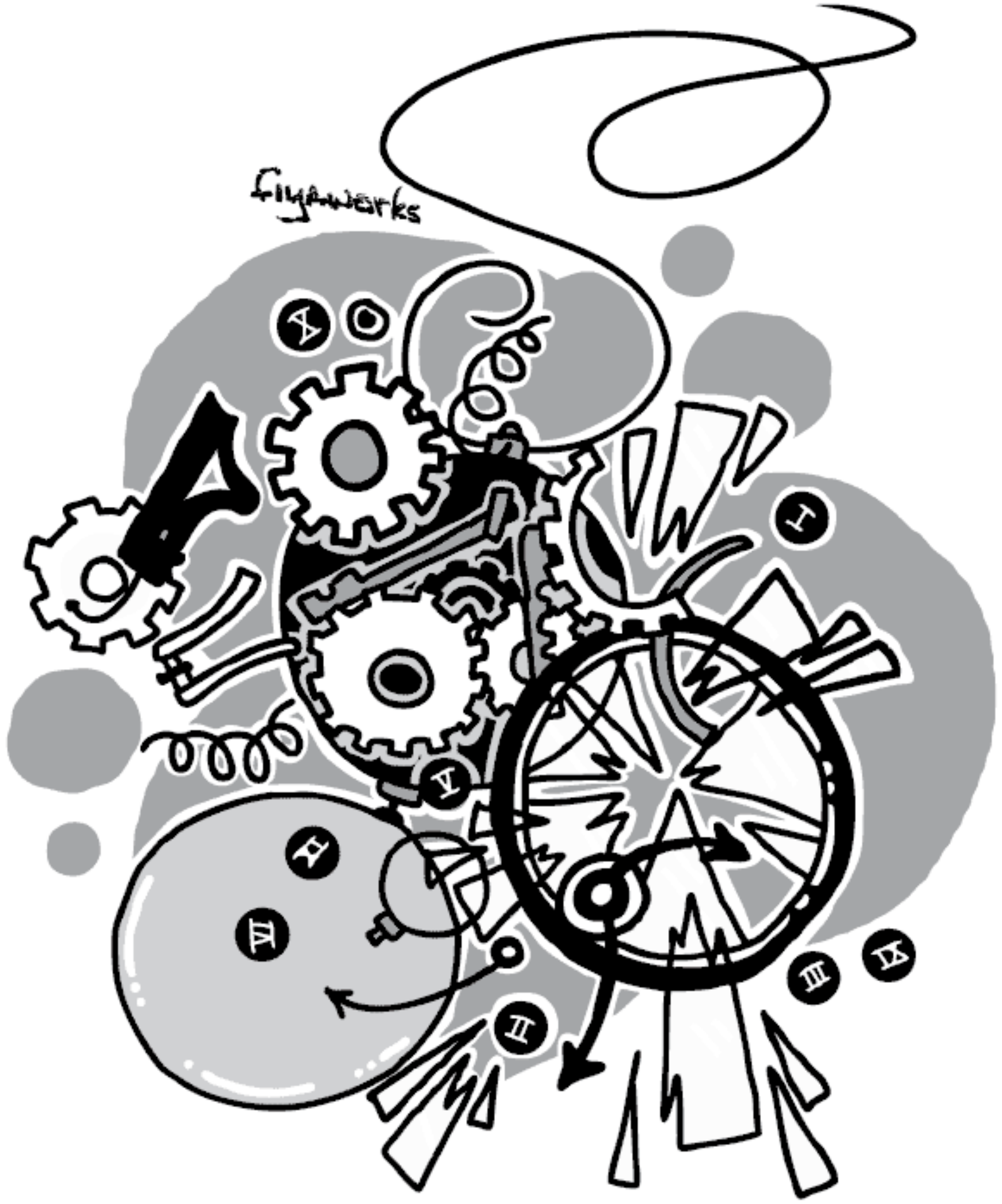
Reading Material

- G. Wolf “HERA Physics” DESY-94-22 (1994),
- EIC White Paper:
  - Electron Ion Collider: The Next QCD Frontier, Eur. Phys. J. A52 (2016) no.9, 268 arXiv:1212.1701
- EIC Yellow Report:
  - Science Requirements and Detector Concepts for the Electron-Ion Collider : EIC Yellow Report, *Nucl. Phys. A* 1026 (2022) 122447, arXiv:2103.05419
- The Glue That Bins Us:
  - Scientific American (May 2015), by R. Ent, R. Venugopalan, TU
- The Deepest Recesses of the Atom
  - in Scientific American Magazine Vol. 320 No. 6 (June 2019), p. 32 by A. Deshpande & R. Yoshida

Outline of Lectures

- **Lecture I - Tuesday, July 2, 9:00-10:00**
  - Probing Matter
  - Kinematics & Structure Functions
  - Frontiers if our Ignorance
- **Lecture II - Wednesday, July 3, 14:30-15:30**
  - What Do We Need?
  - Example of Physics Measurements at the EIC
    - Spin of the Proton
    - Diffractive Physics
    - Dihadron Correlations
    - Imaging
    - Structure Functions and PDFs
- **Lecture III - Thursday, July 4, 13:30-14:30**
  - Realization of an EIC: the Collider
  - Realization of an EIC: the Detector
    - The Basics - Detector Technologies
- **Lecture IV - Friday, July 5, 13:30-14:30**
    - Designing an EIC Detector
    - The ePIC Detector
  - Quo Vadis EIC

1.Probing Matter



Scattering of protons on protons is like colliding Swiss watches to find out how they are build.

R. Feynman

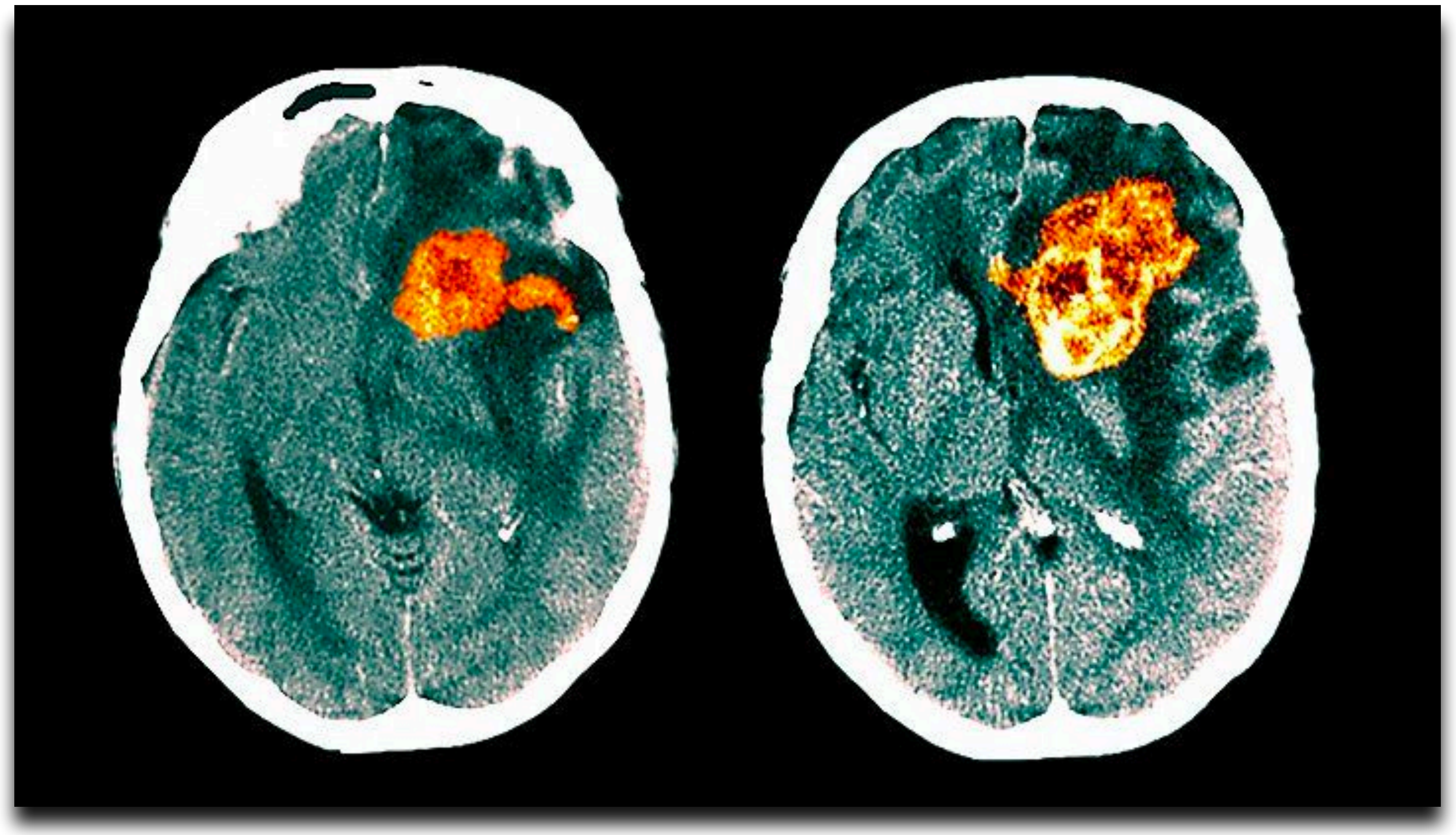
Seeing is Believing – the Power of Imaging

Imaging: one of the most convincing scientific methods to understand our nature!

38 billion km (~10^{12}m)

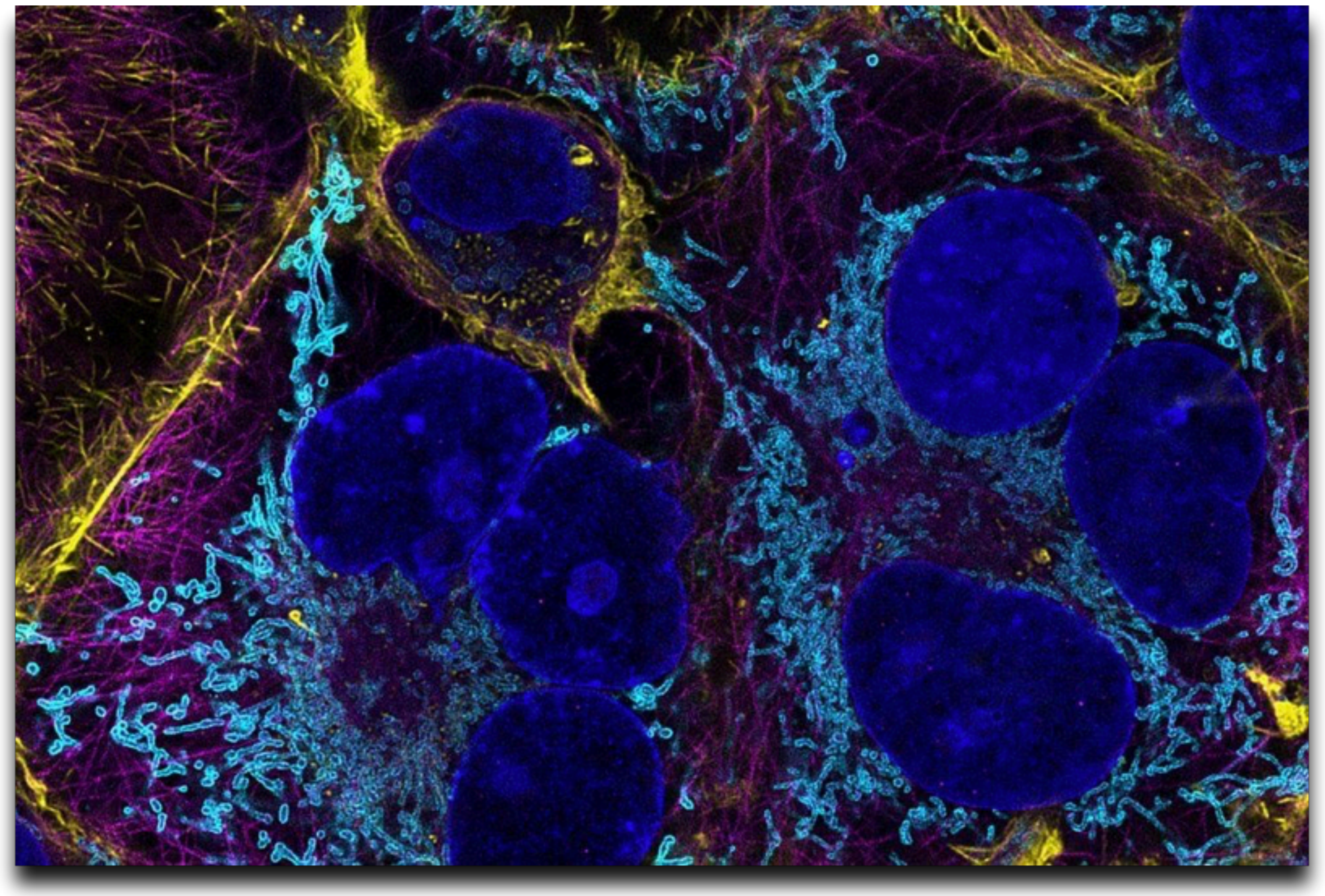
First-ever image of a black hole - *Event Horizon Telescope*

a few centimeter (~10^{-2} m)



CT scan sequence of a patient with a *glioblastoma*.

10-100 nanometer (~10^{-9} m)



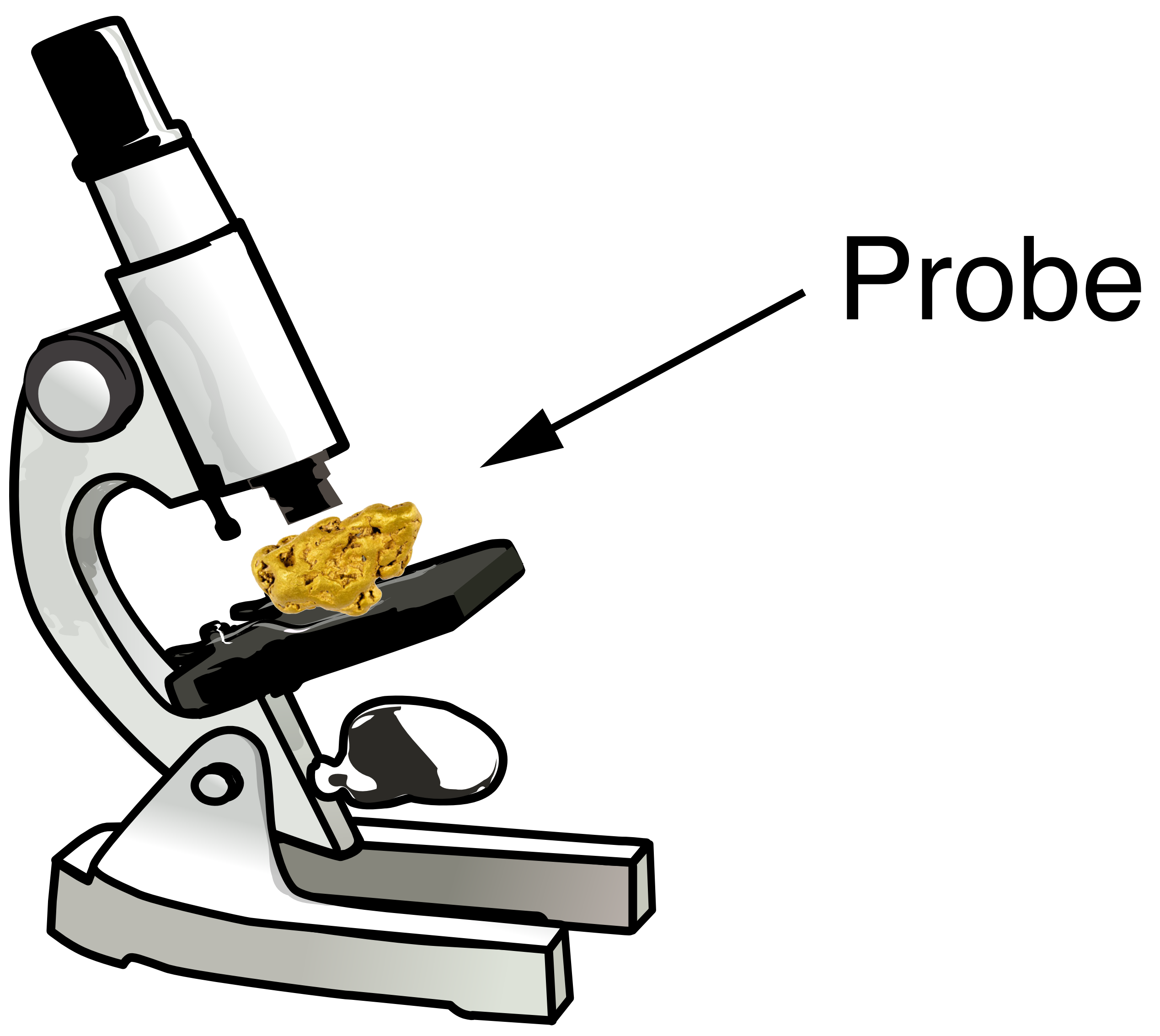
3D images of myelin - the insulation coating our nerve fibres

Astronomical scale

microscopic scale

Studying Matter at Small Scales

Light Microscope
Wave length: 380-740 nm
Resolution: > 200 nm



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Light Microscope
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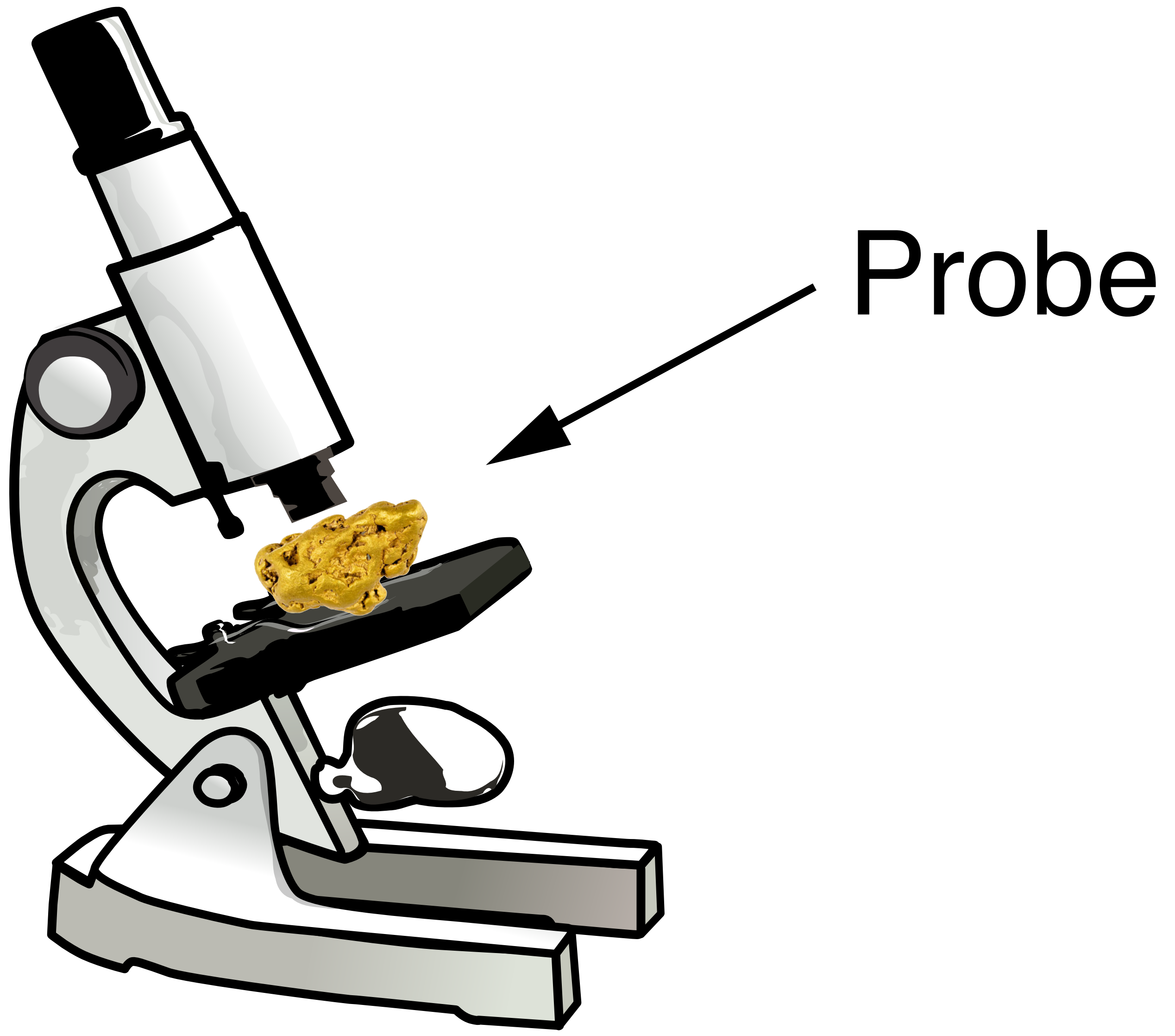
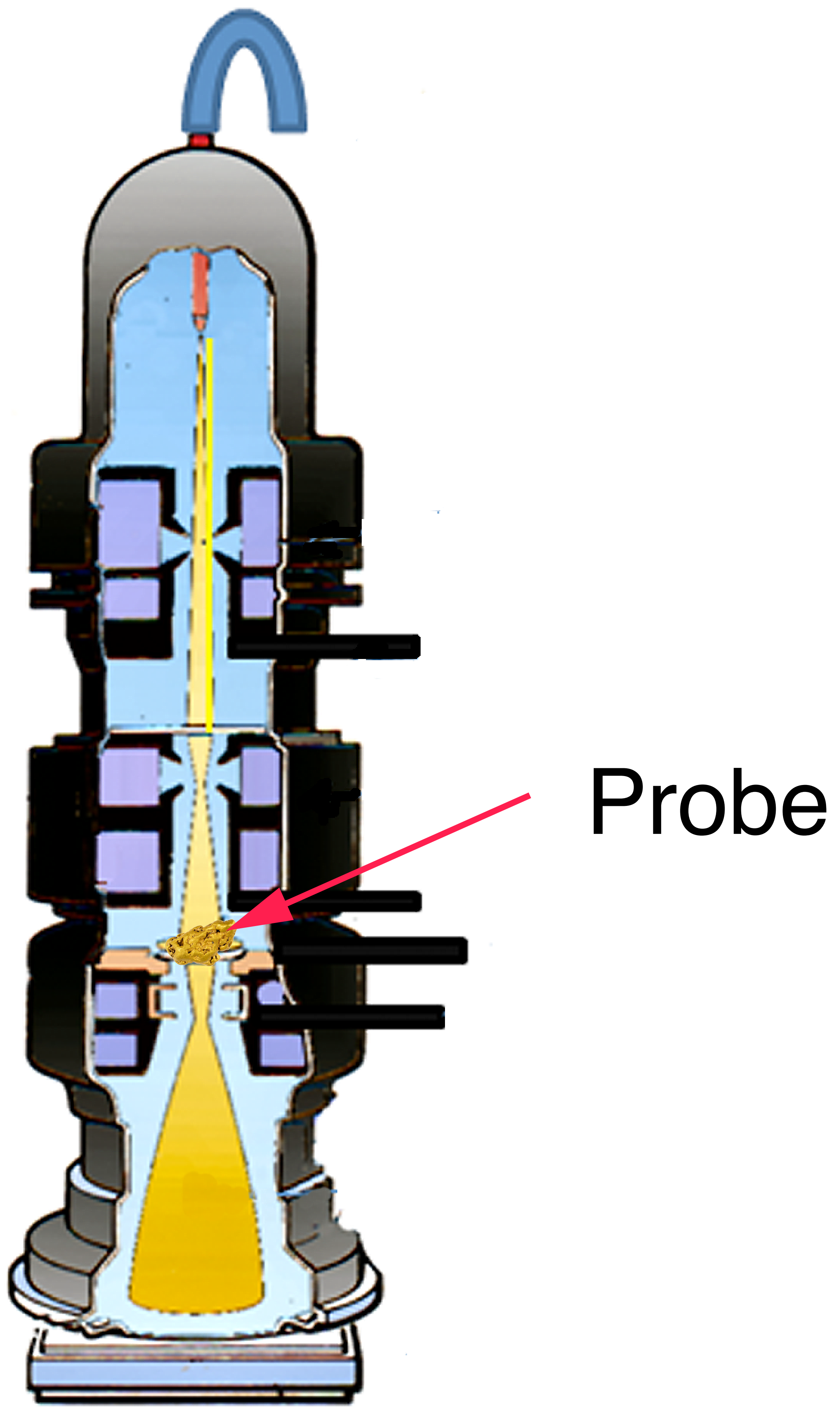
Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm





Studying Matter at Small Scales

Light Microscope
Wave length: 380-740 nm
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Wave length: 0.002 nm (100 keV)
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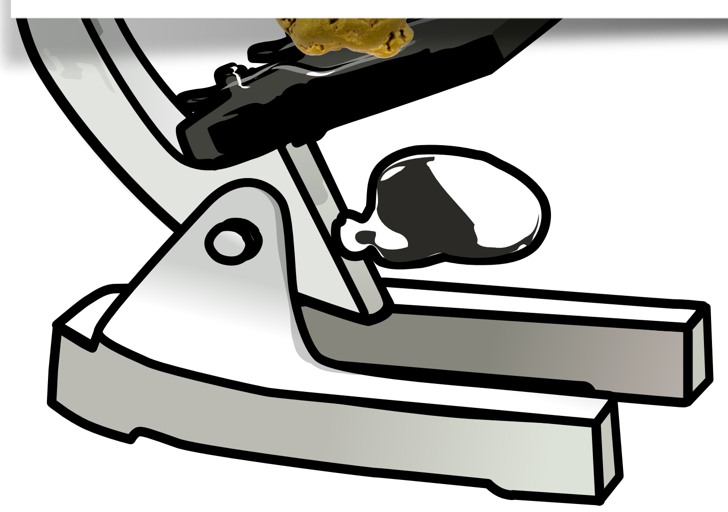
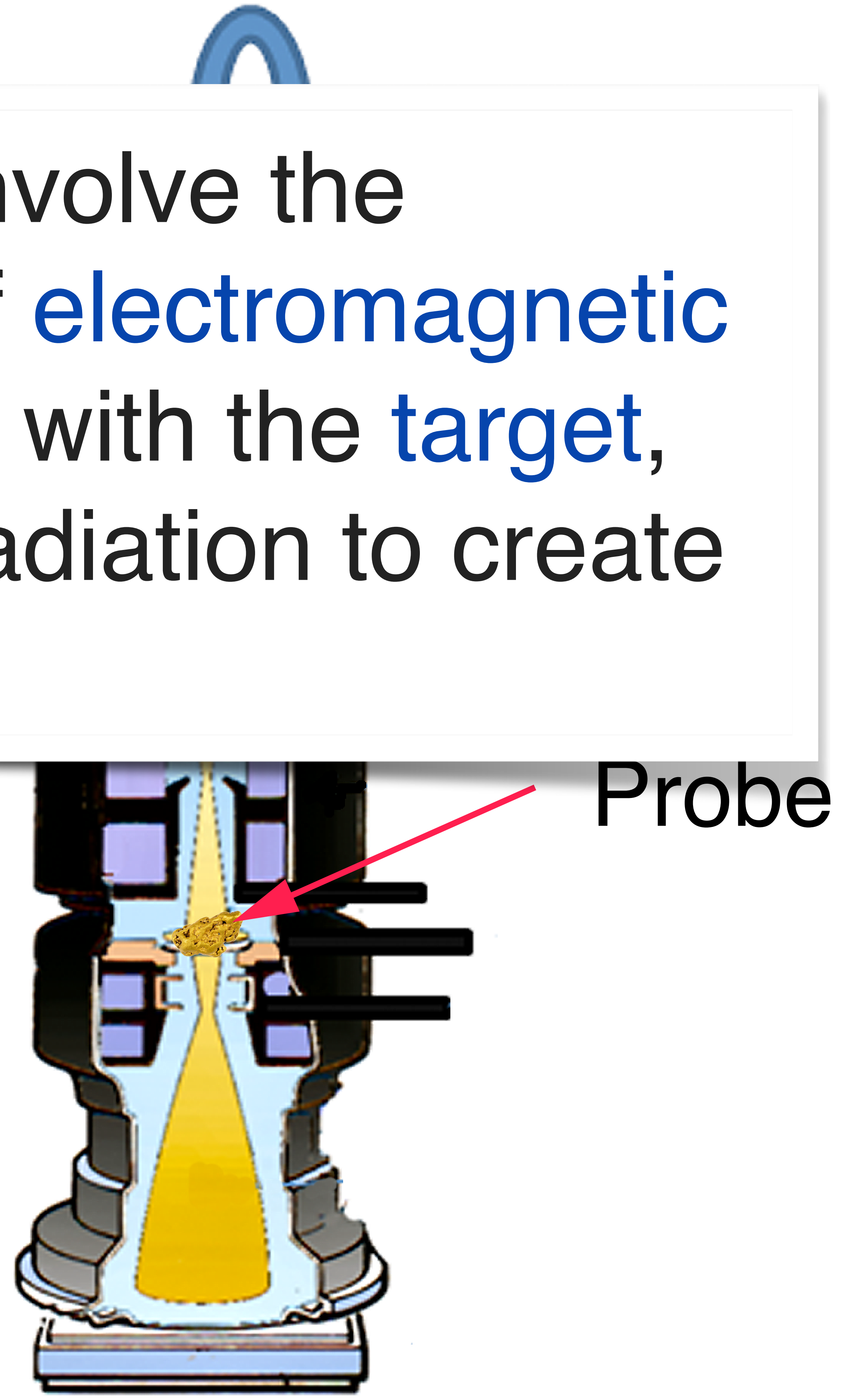
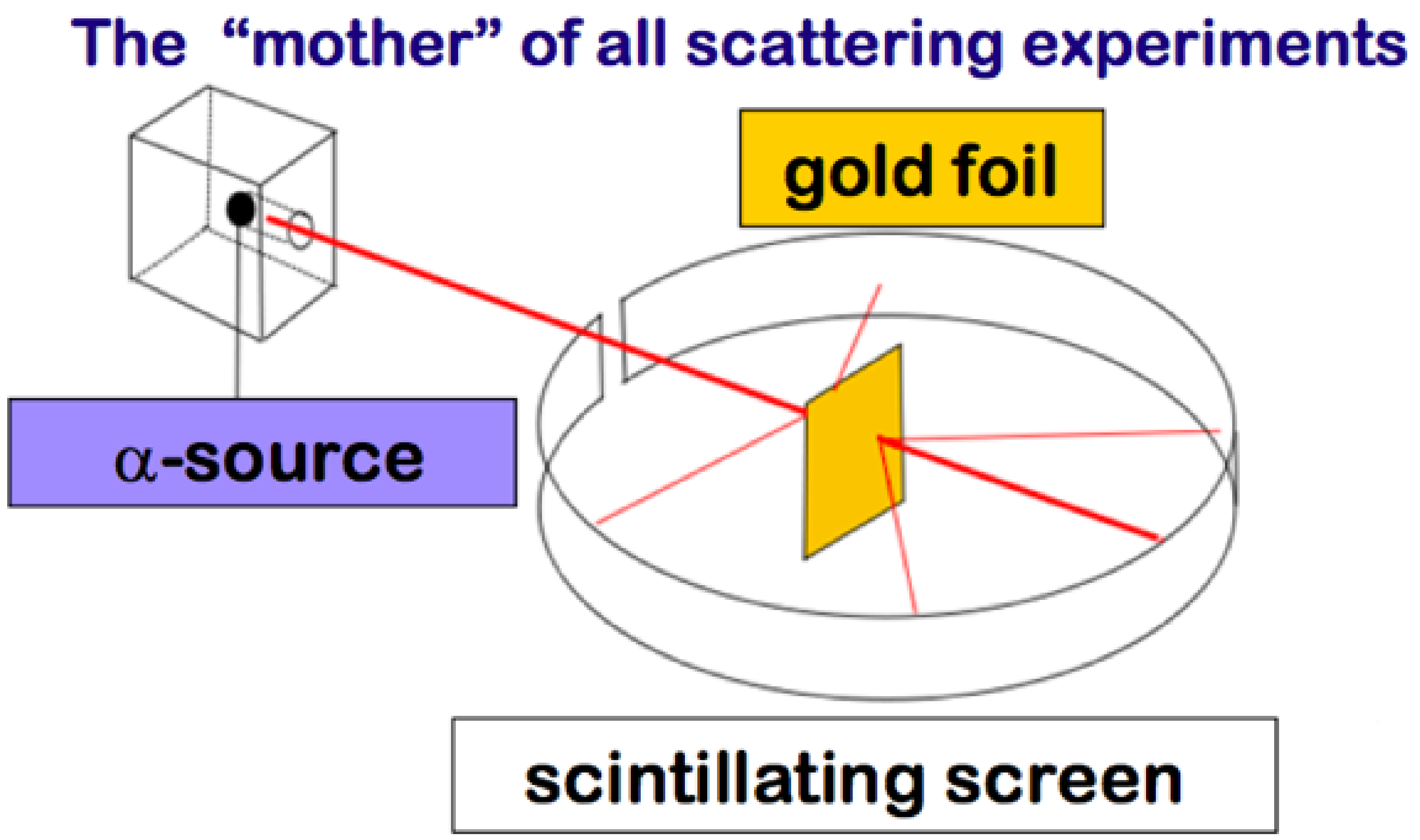
Note: Optical/electron microscopy involve the diffraction, reflection, or refraction of electromagnetic radiation/electron beams interacting with the target, and the collection of the scattered radiation to create an image. They don't go deep.

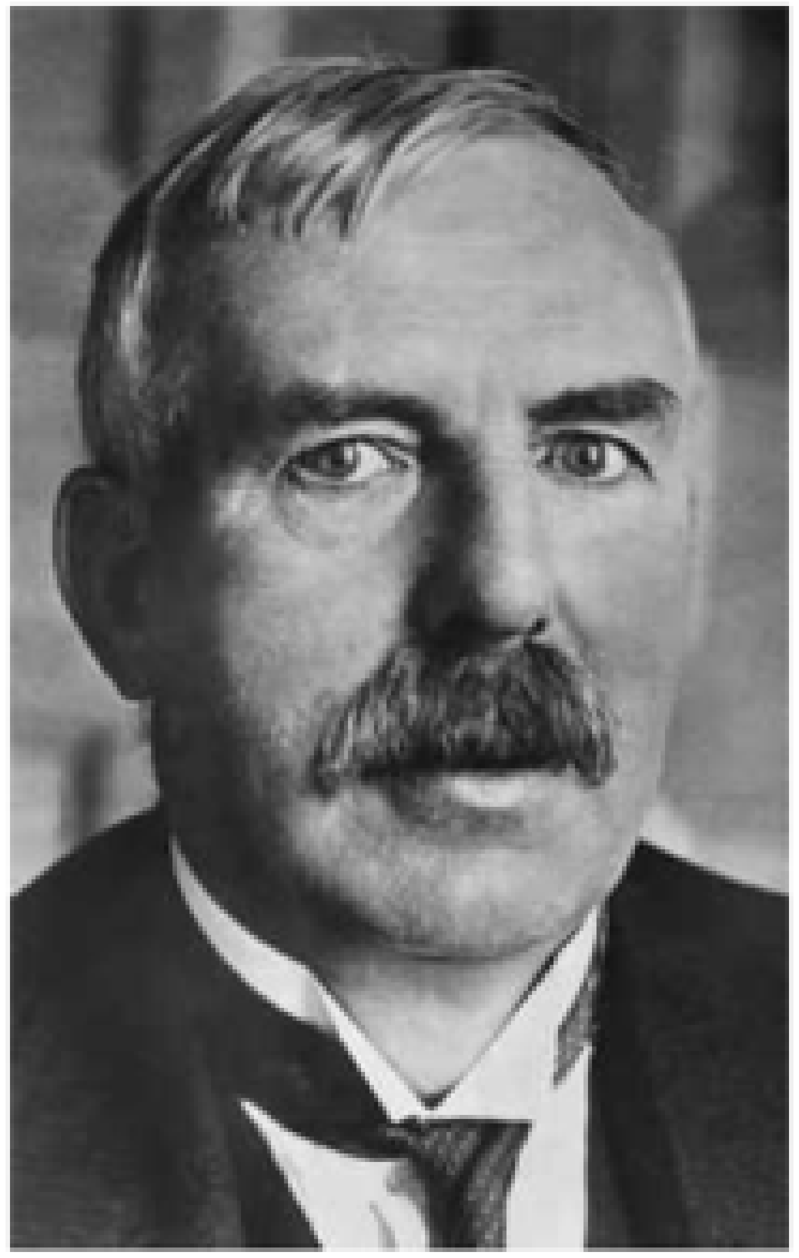




Probing Matter (1909)

The first exploration of subatomic structure was undertaken by Rutherford at Manchester using Au atoms as targets and α particles as probes.





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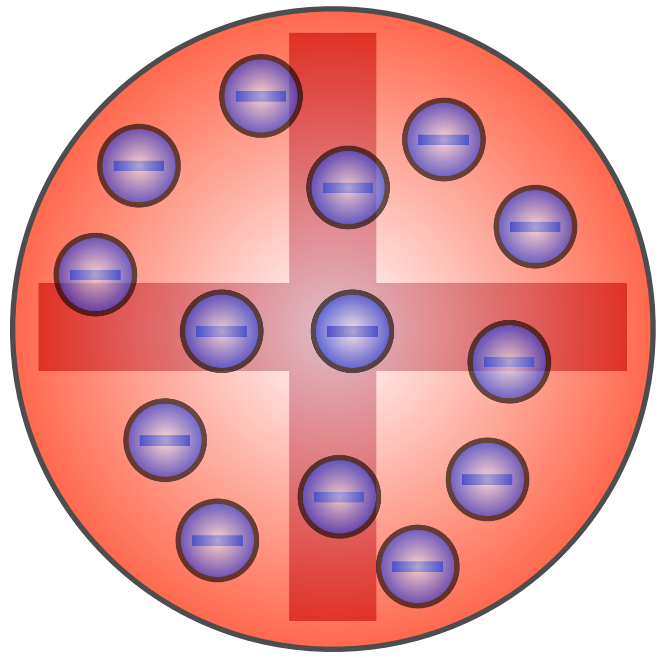
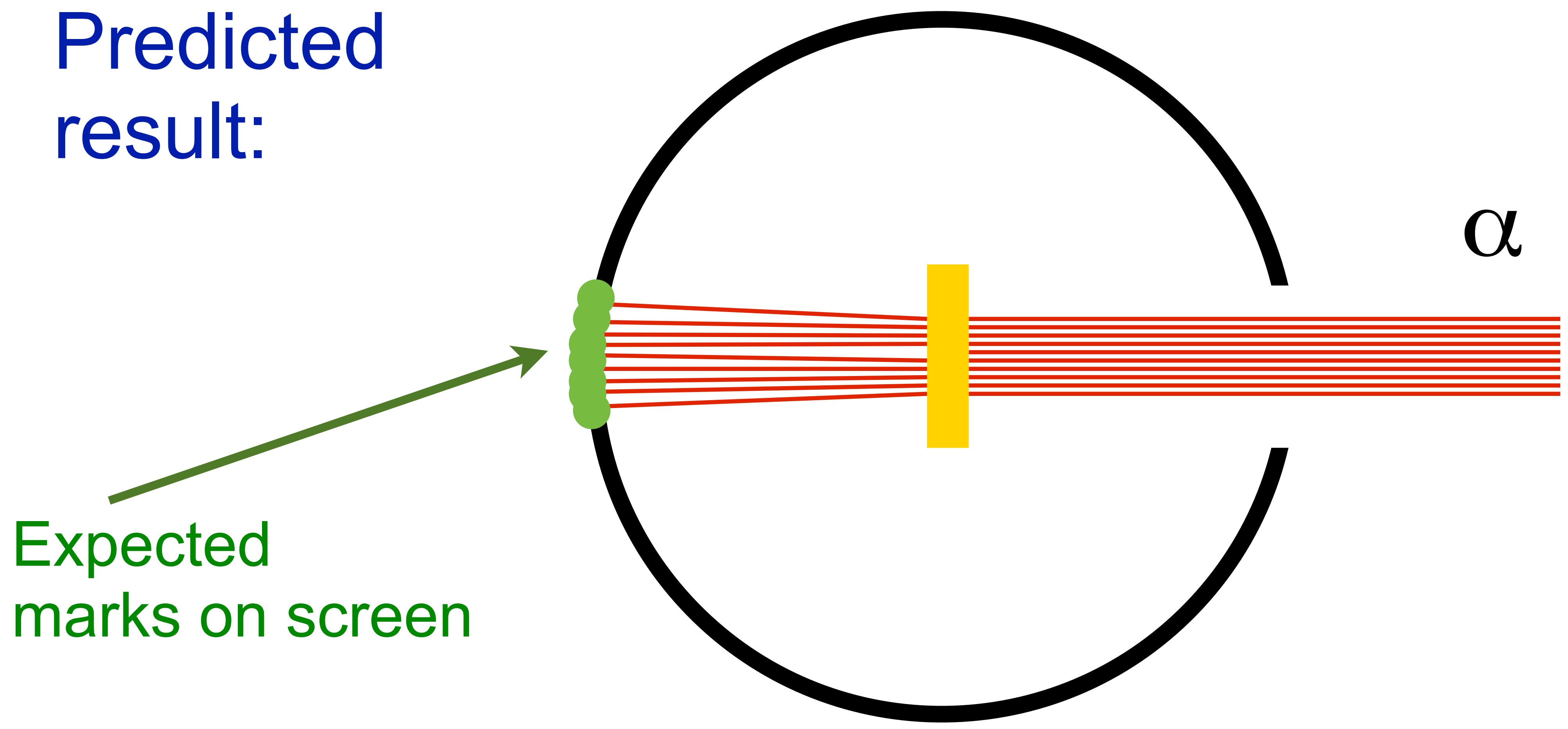
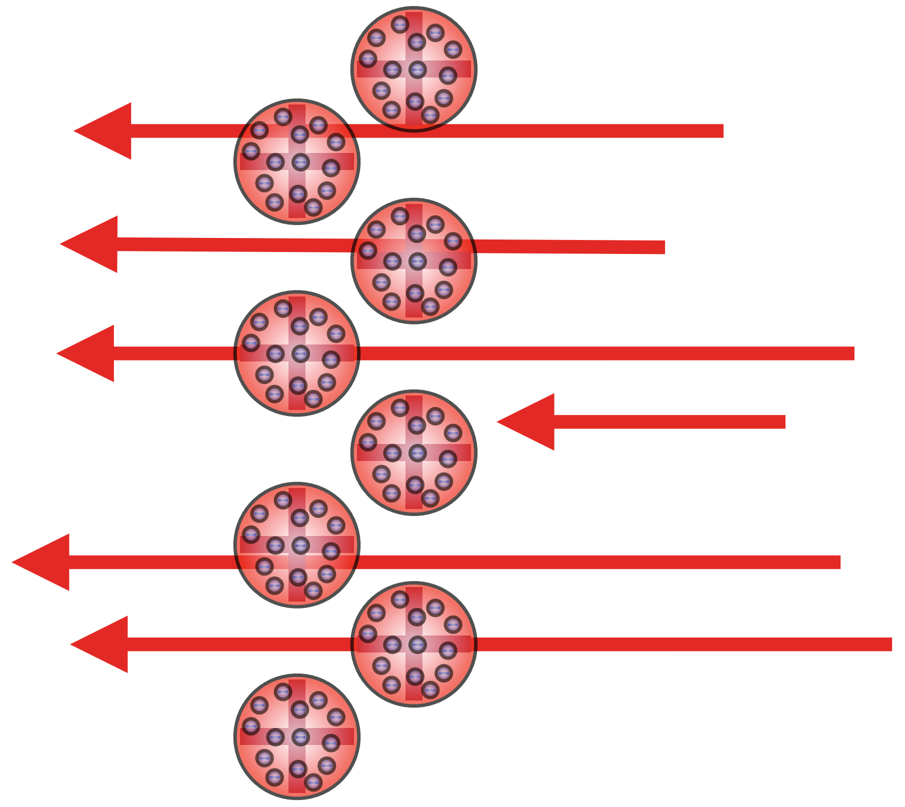


Thomson's
Plum Pudding Model

Predicted
result:



Detail of gold foil (Thomson):



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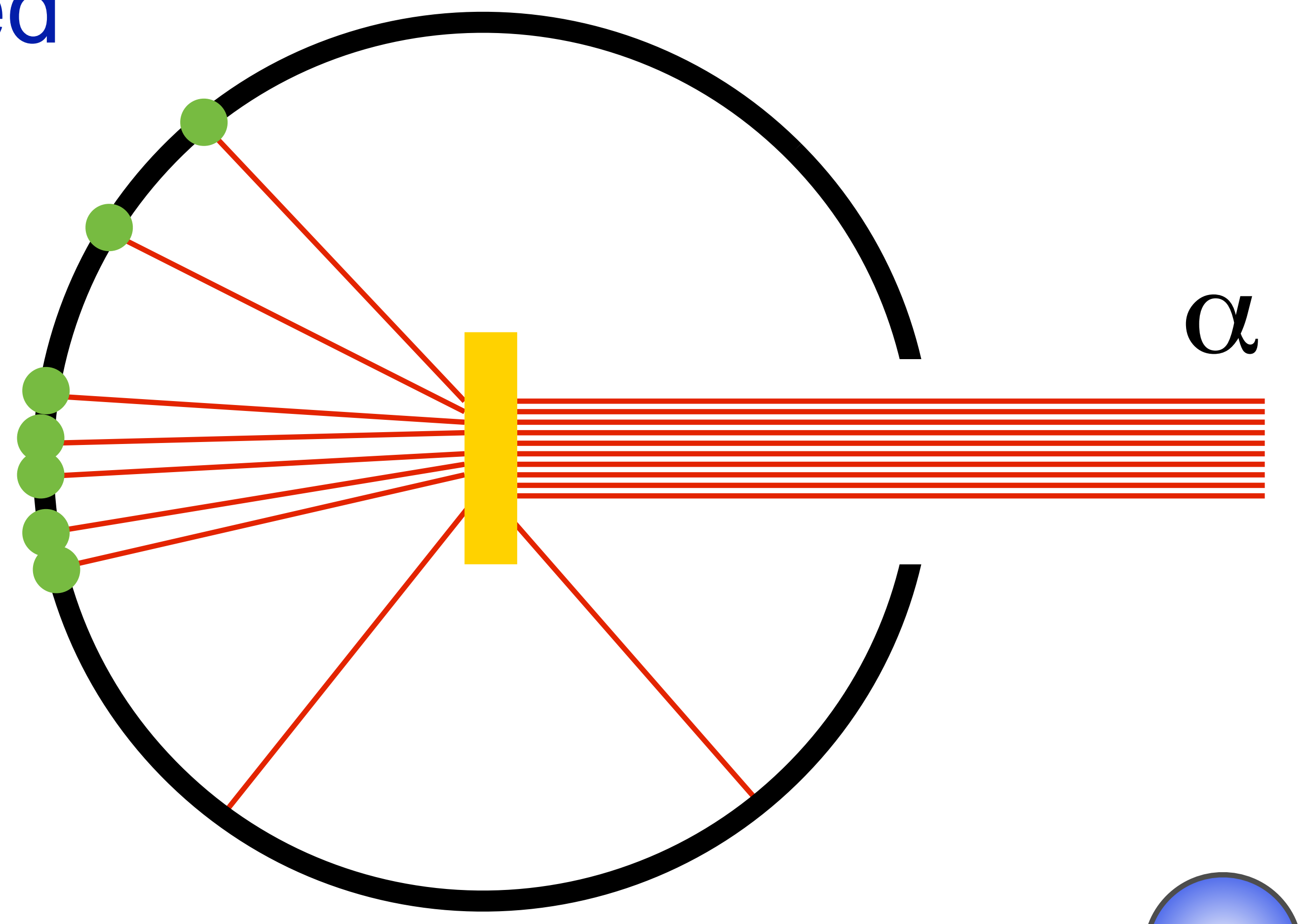
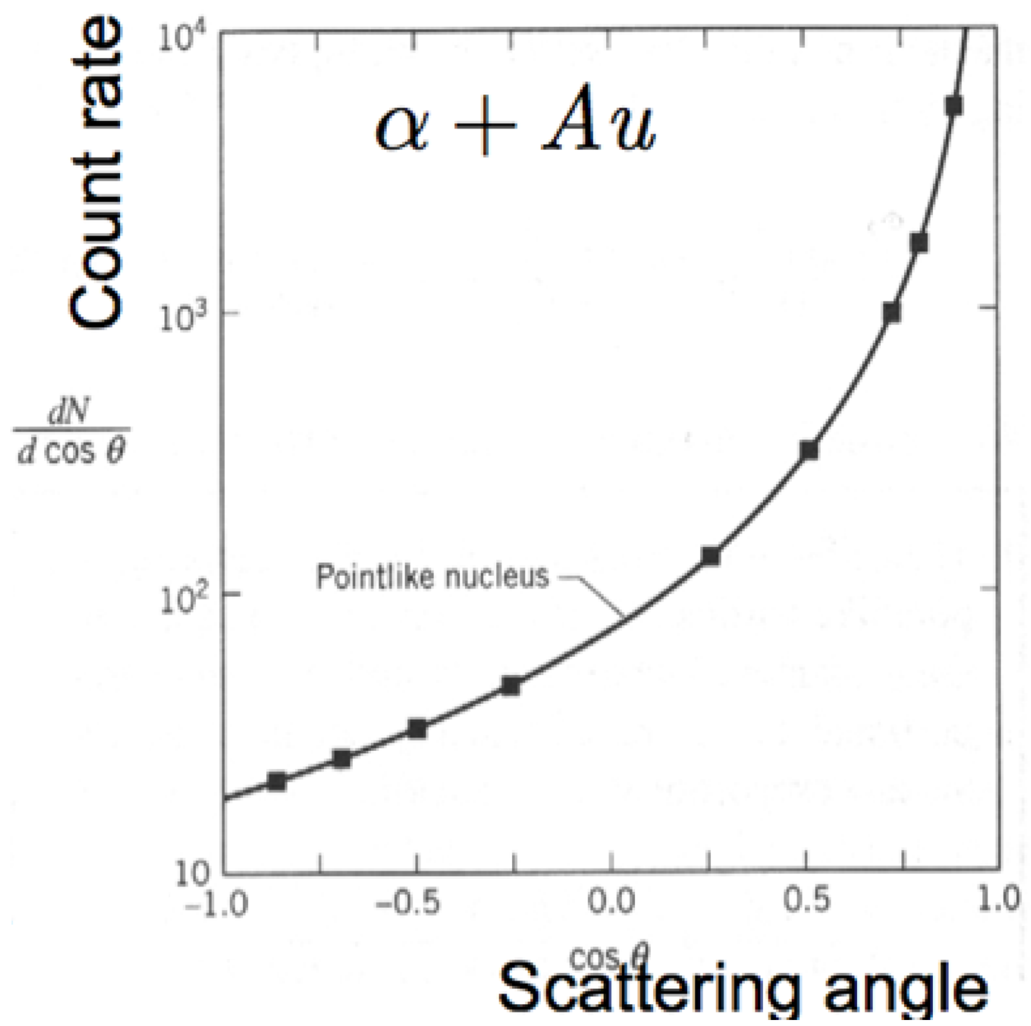
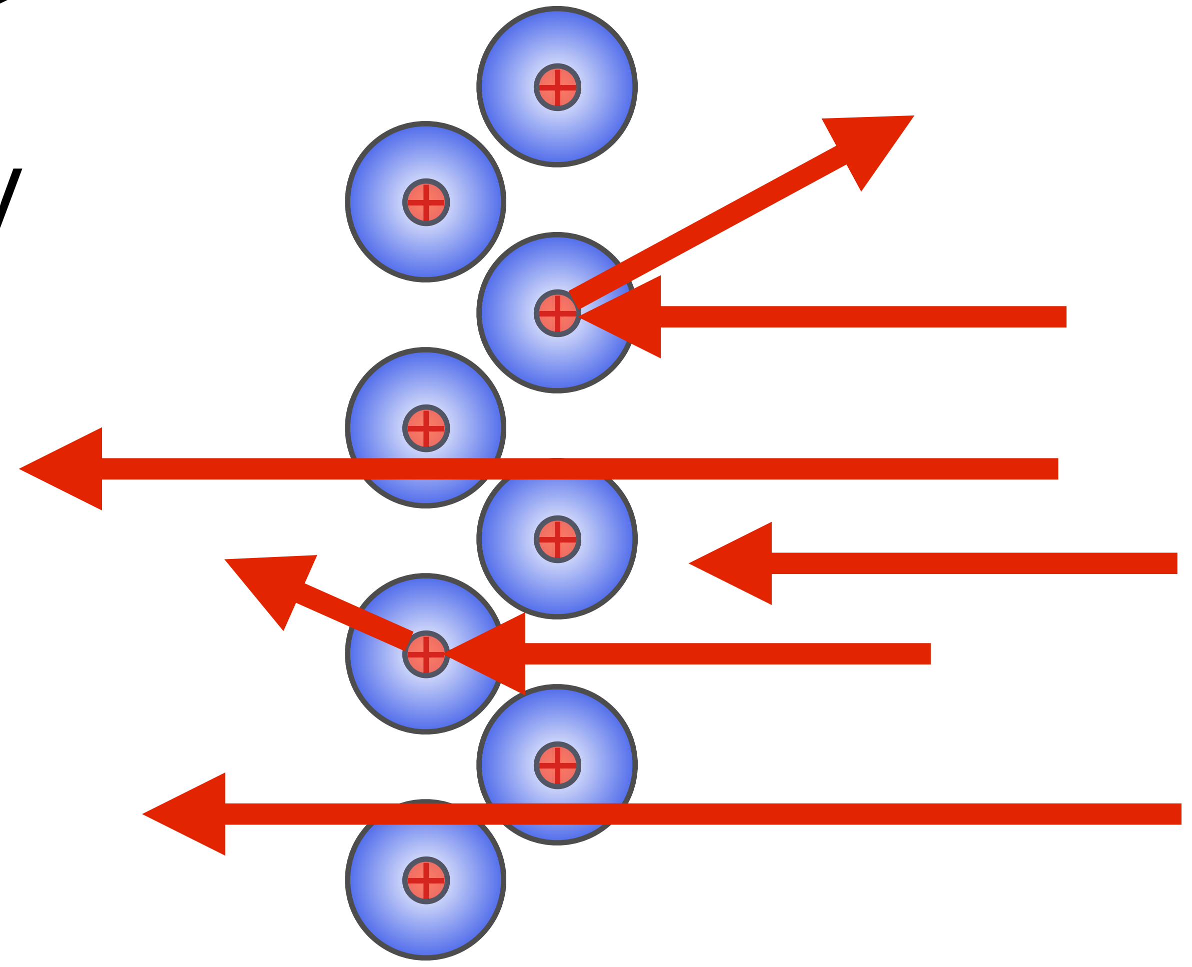
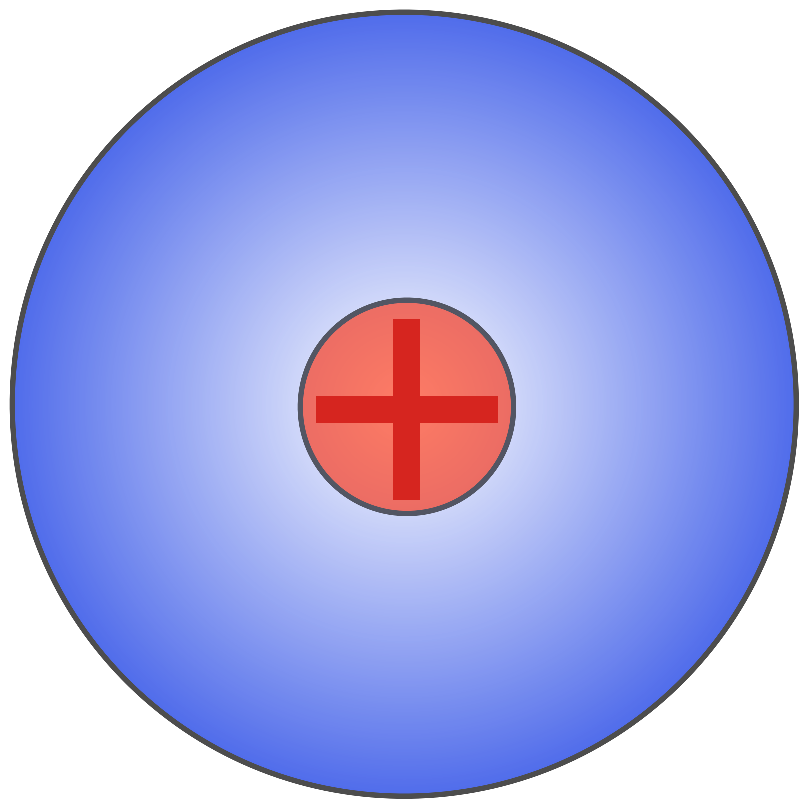
Observed result:





Positive Nucleus Theory explain α deflection:





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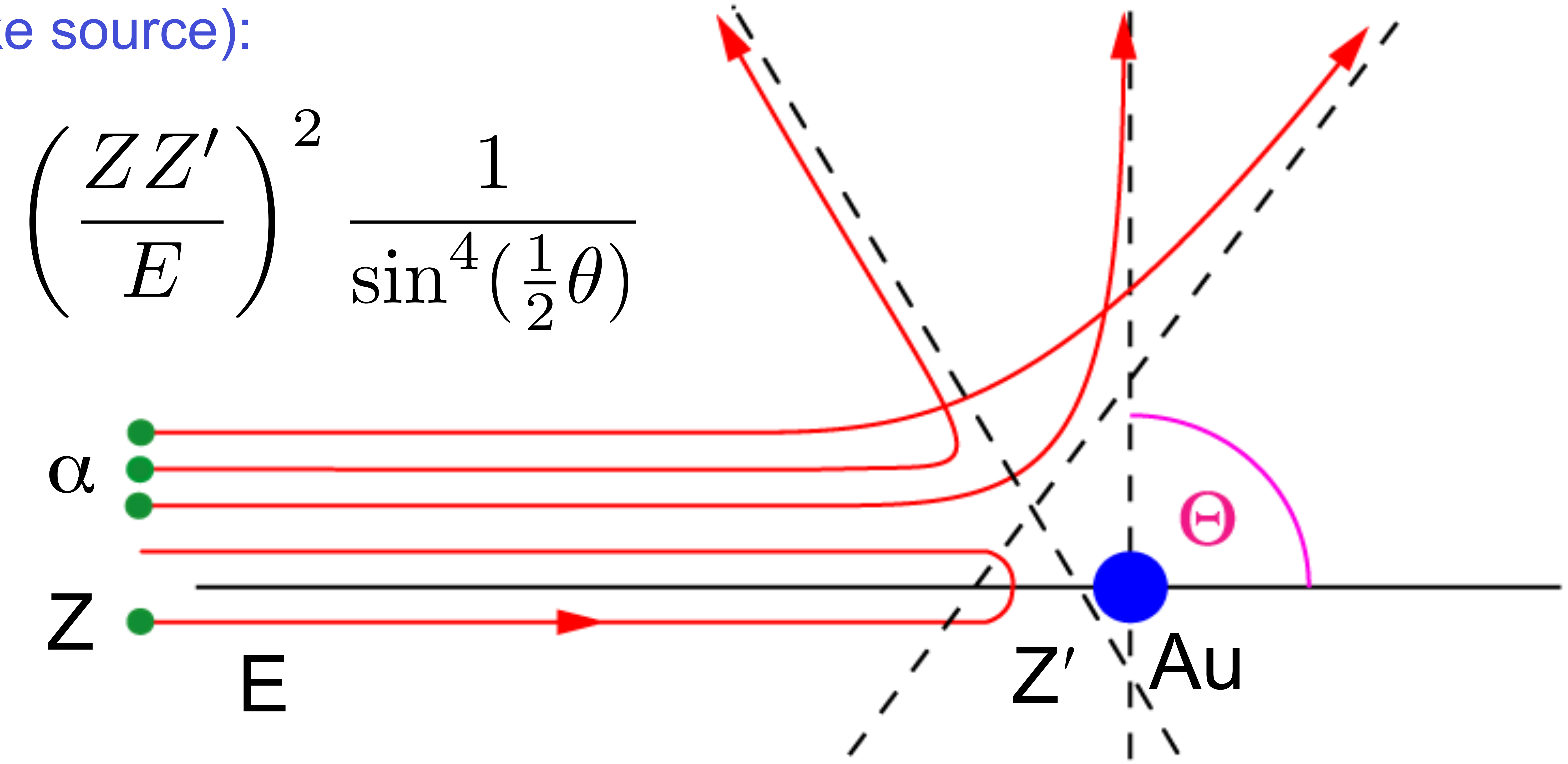
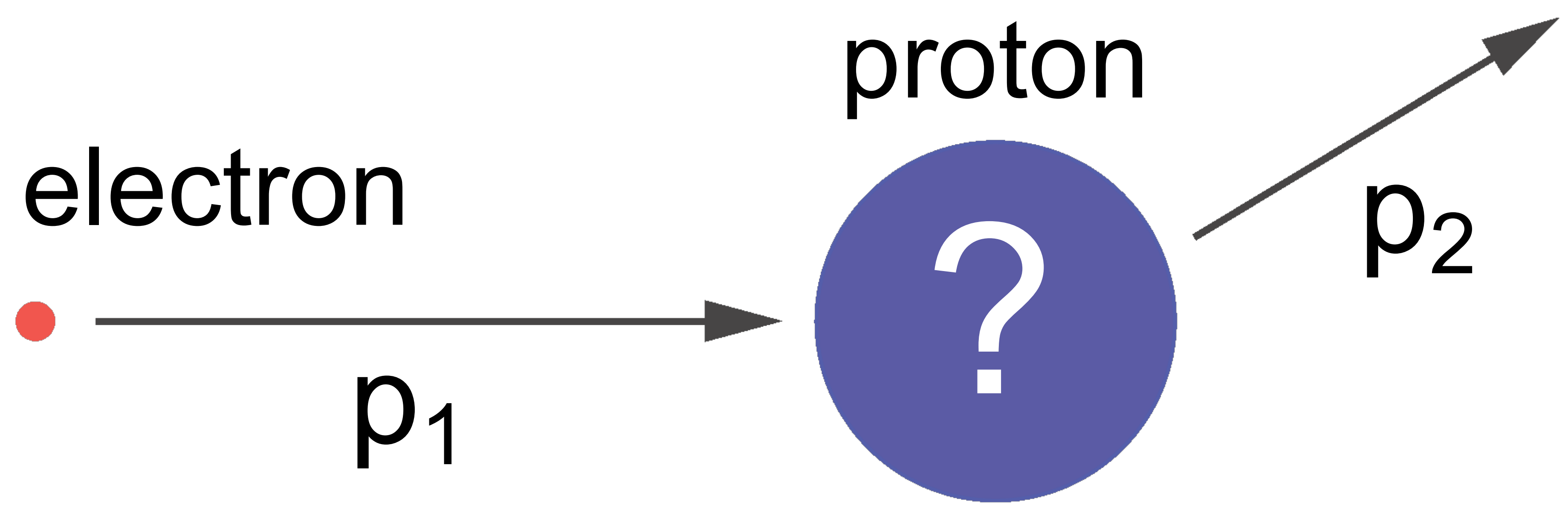
Elastic scattering of charged particles in Coulomb field (point-like source):

$$\frac{d\sigma}{d\Omega} = \left(\frac{ZZ'}{E}\right)^2 \frac{1}{\sin^4(\frac{1}{2}\theta)}$$



Probing Matter with Hard Probes (Electrons)

The SLAC experiments in the 1960s established the quark model and our modern view of particle physics.



Mott = Rutherford + Spin

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} |F(q^2)|^2$$

$$q^2 = (\mathbf{p}_1 - \mathbf{p}_2)^2$$

Formfactor: $F(q^2)$

Fourier transform of charge distributions

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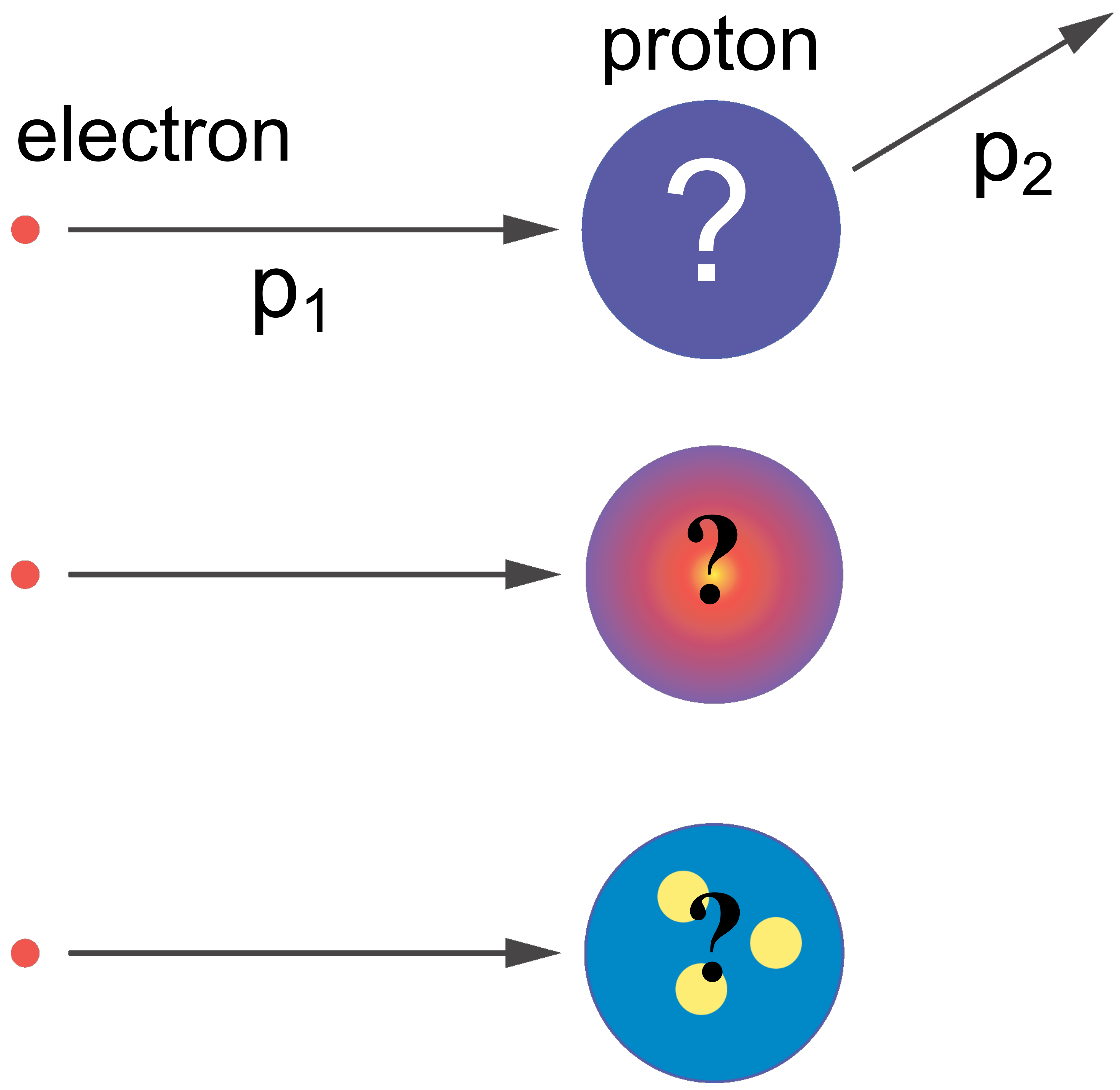

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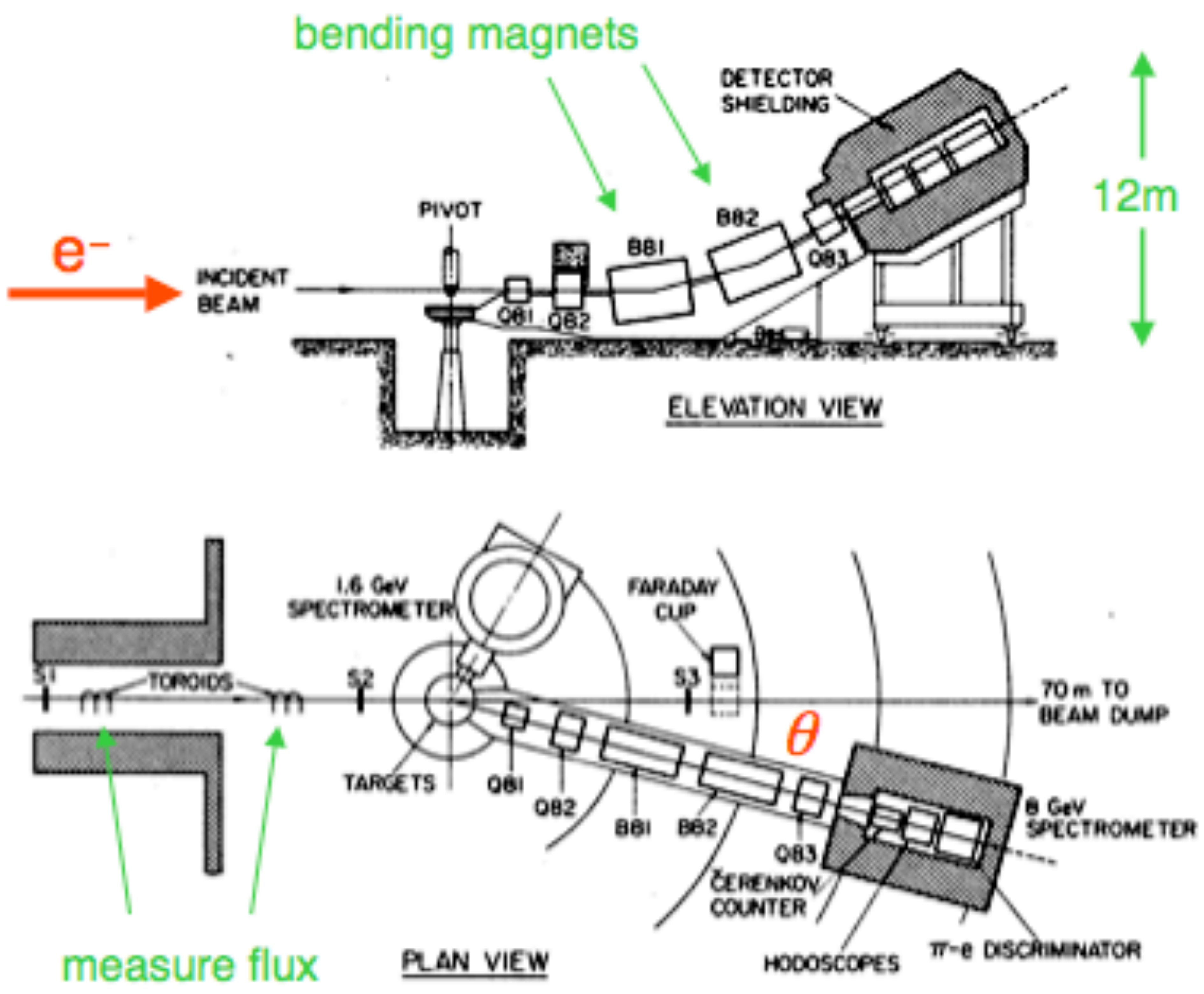

Scattered electron is deflected by a known *B*-field and a fixed vertical angle:

determine *E'*

Spectrometer can rotate in the horizontal plane,

vary θ

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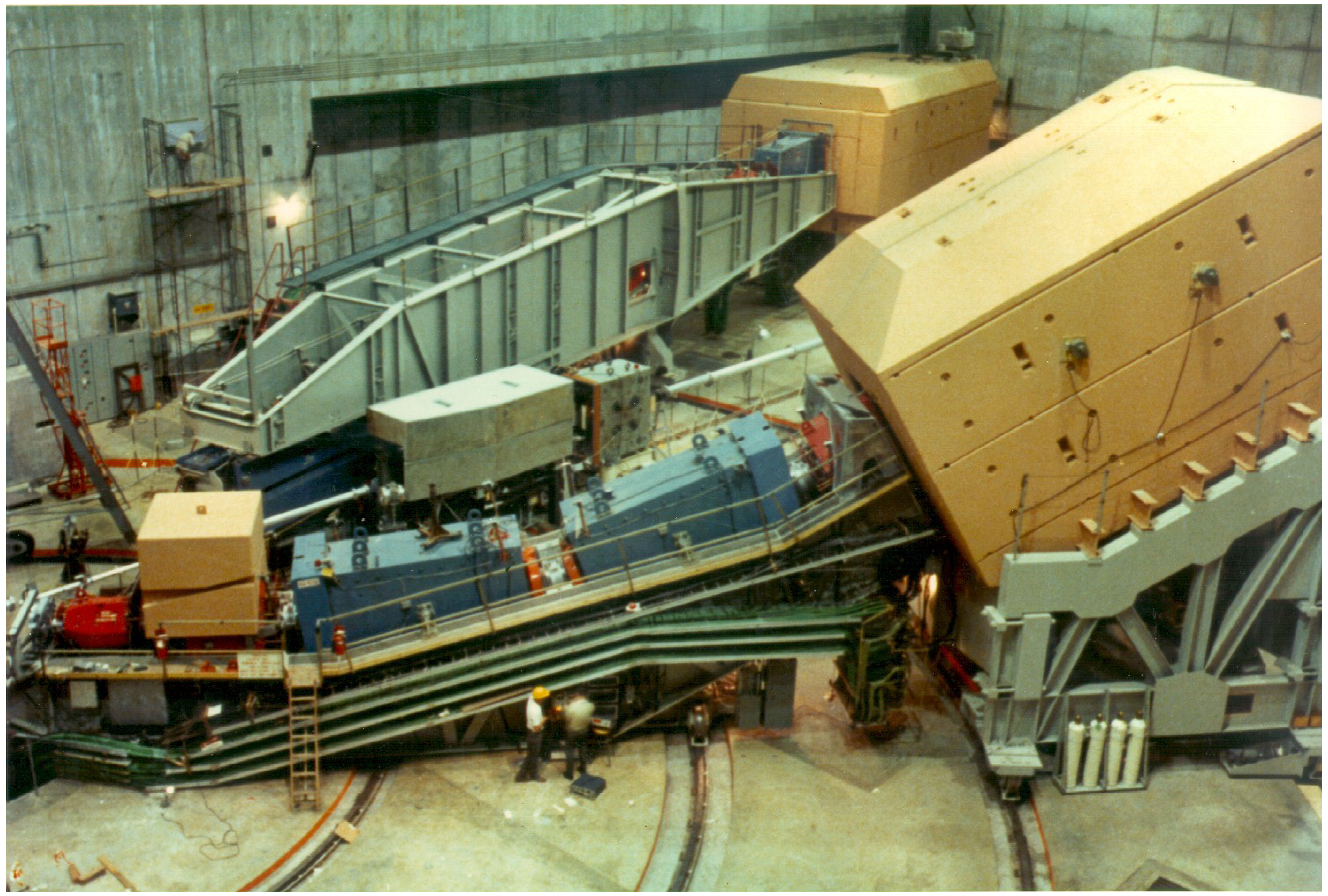

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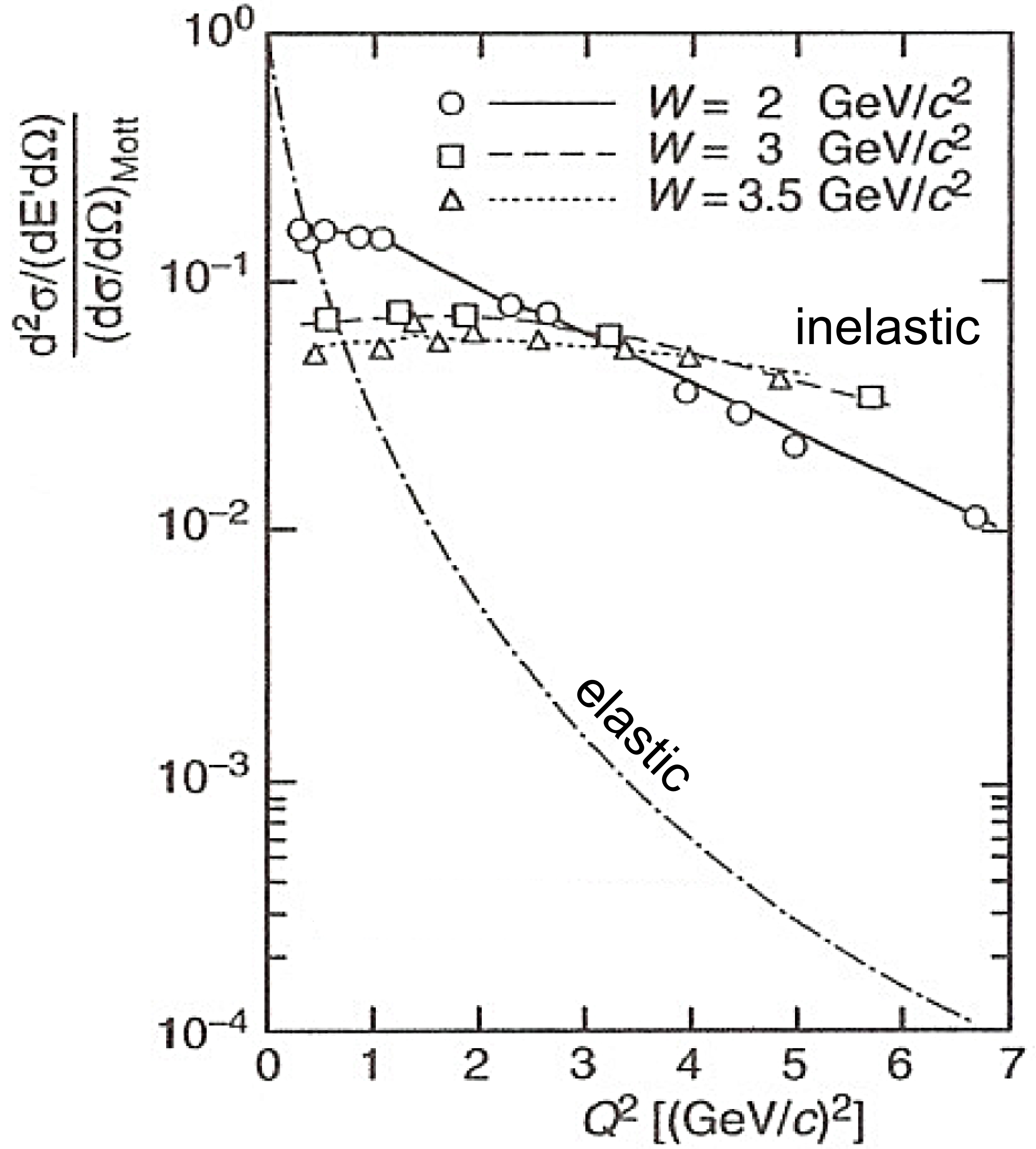
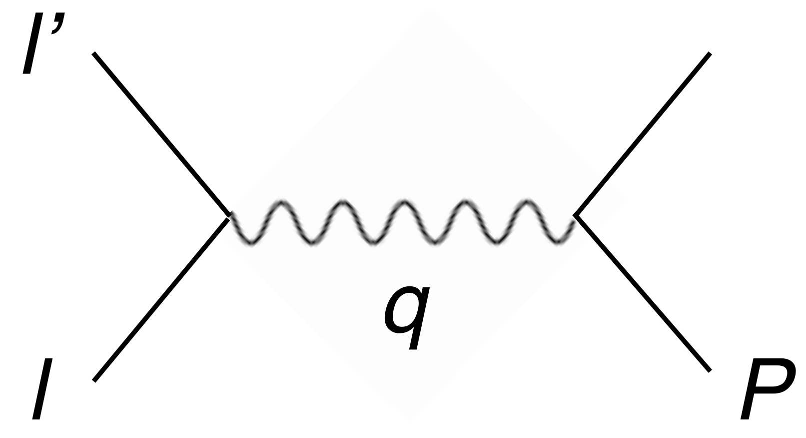
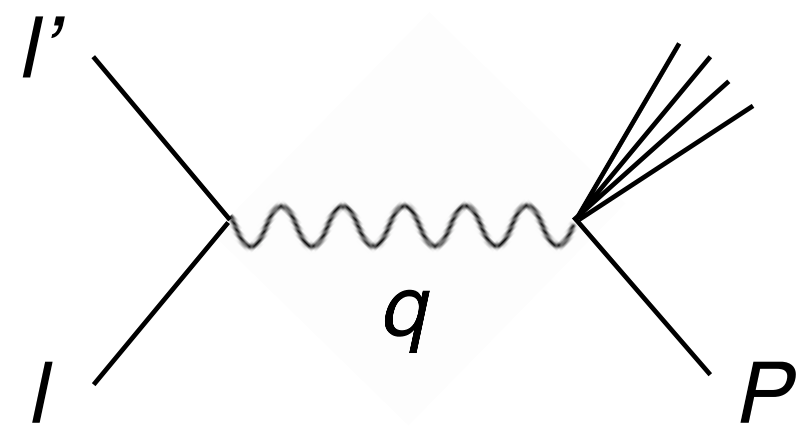


elastic:



inelastic:



Constant $F(q^2)$:

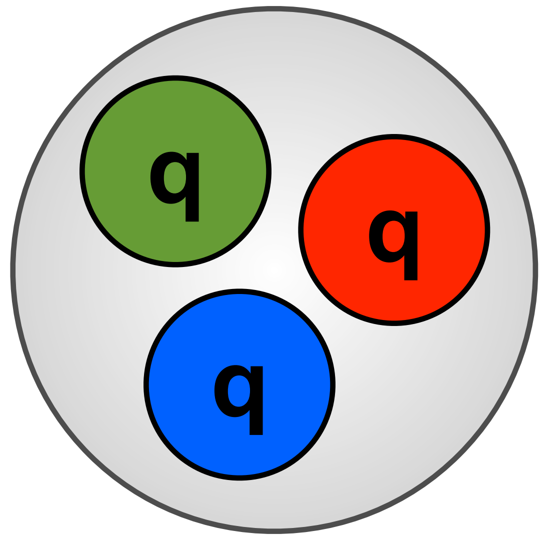
⇒ scattering on point-like constituent of the nucleon

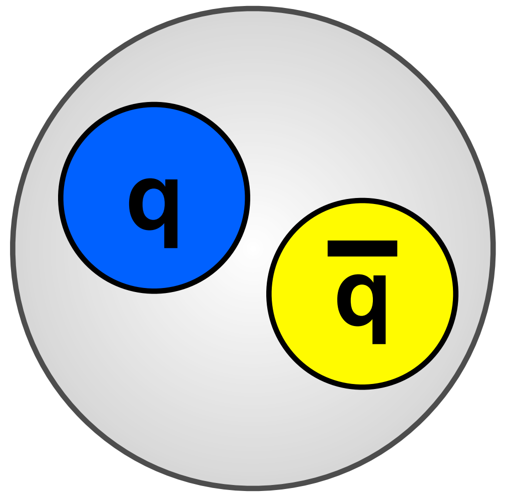
⇒ quarks

“Static” Quark Model

Quarks: spin 1/2 fermions, color charge

M. Gell-Mann,
K. Nishijima (> 1964)

Baryons: 

Mesons: 

Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	$+1$	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	$+1$

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M. Gell-Mann,
K. Nishijima (> 1964)

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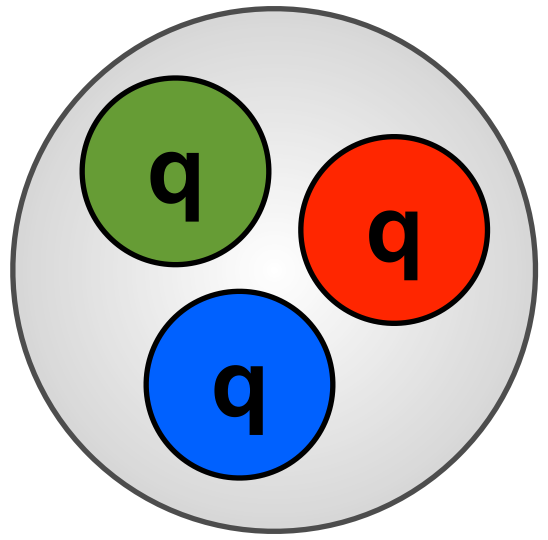
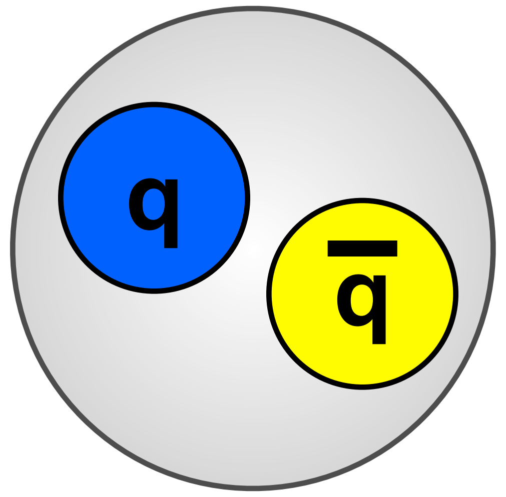
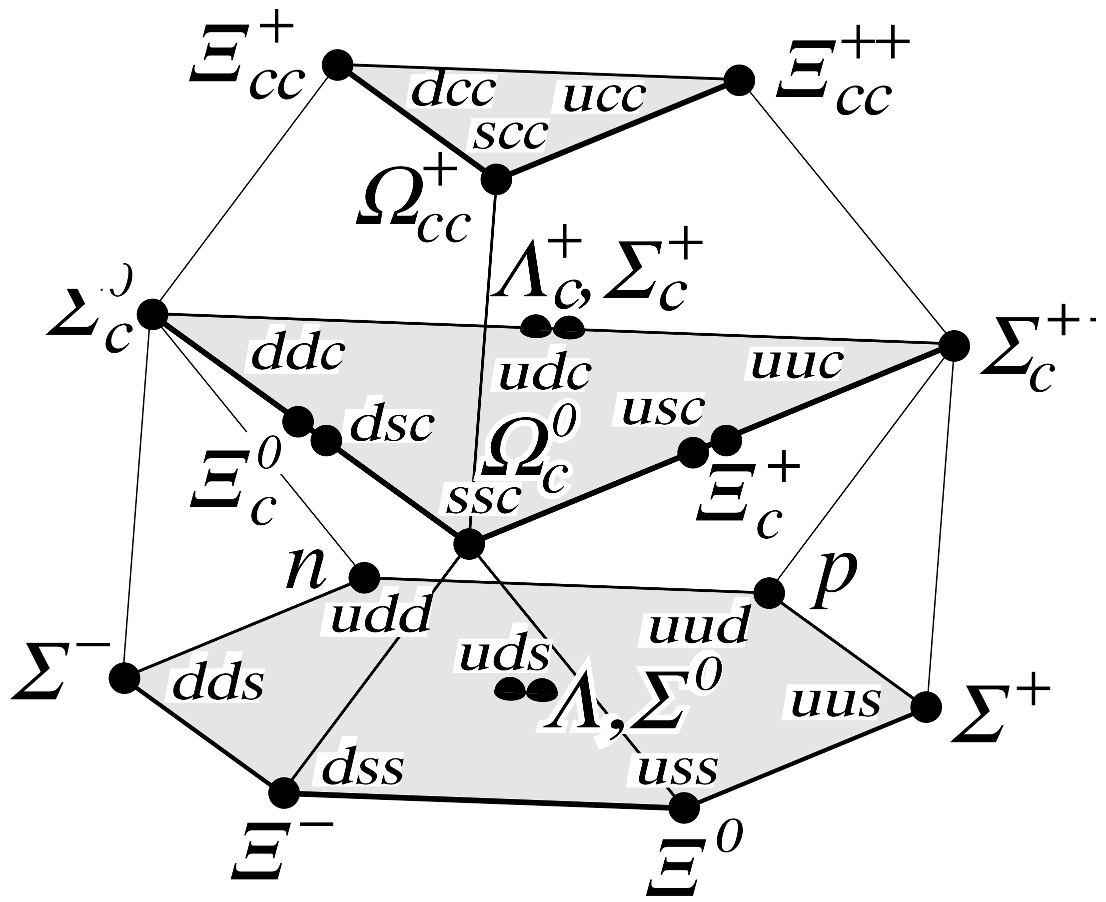
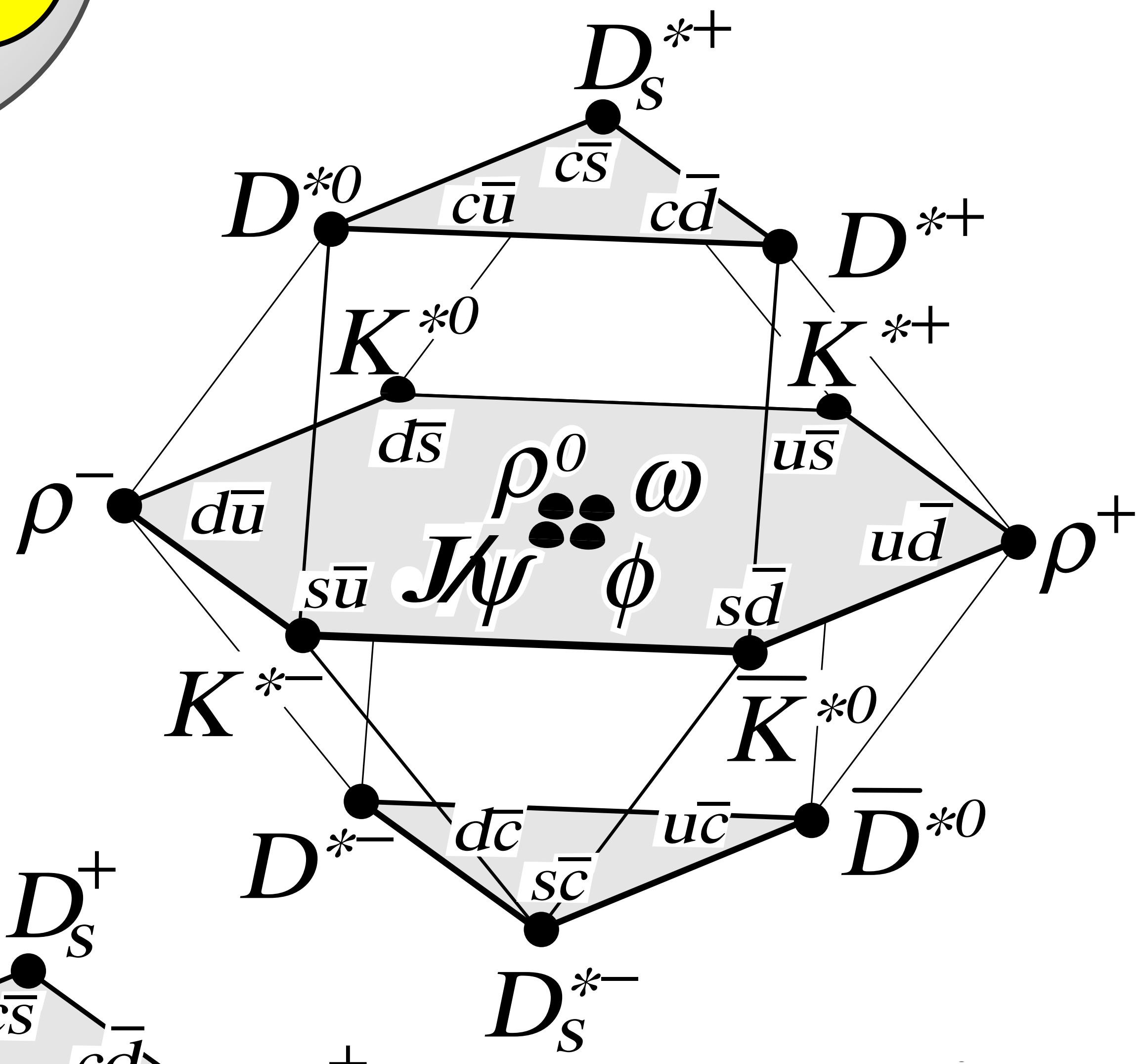


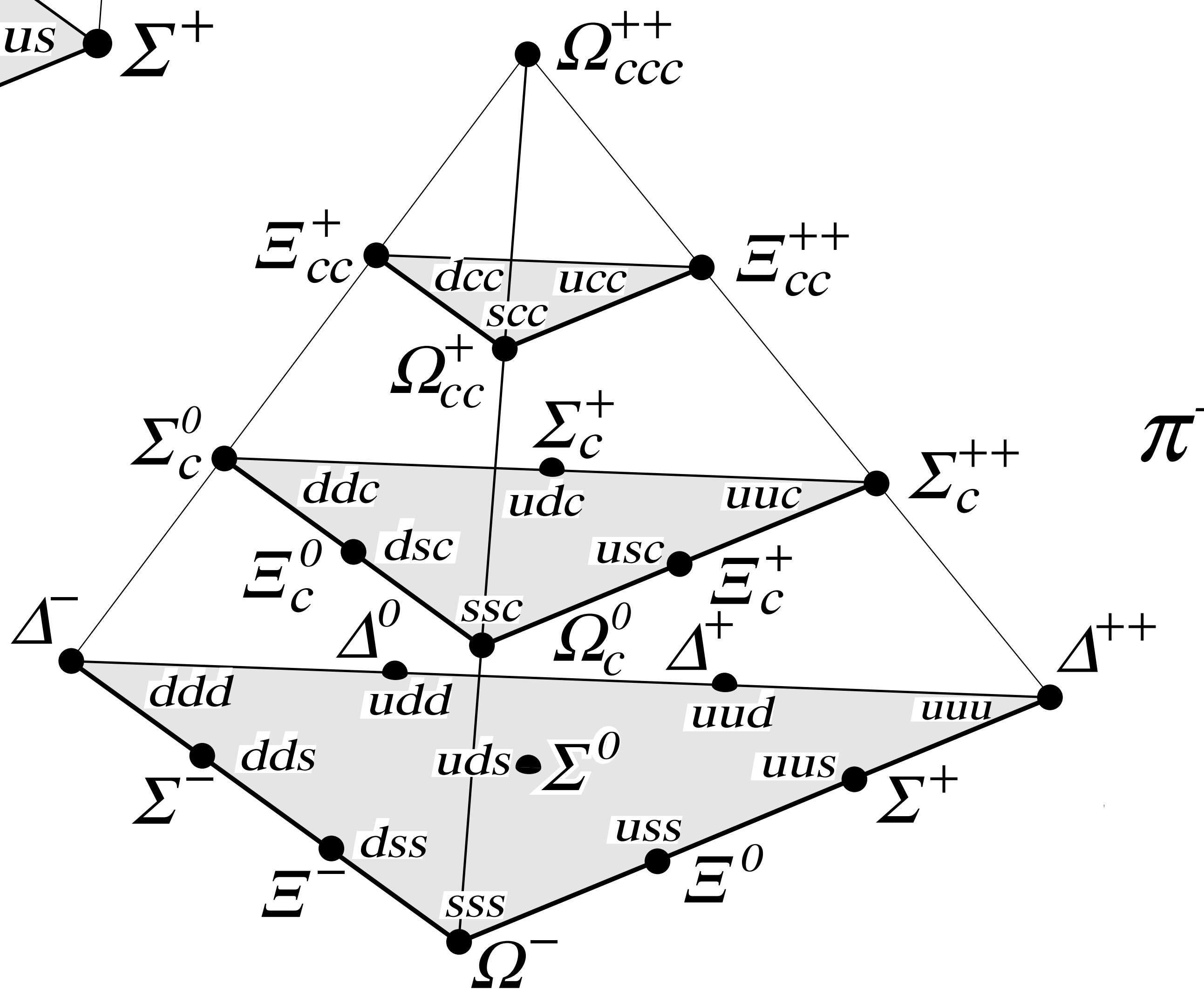
Mesons:

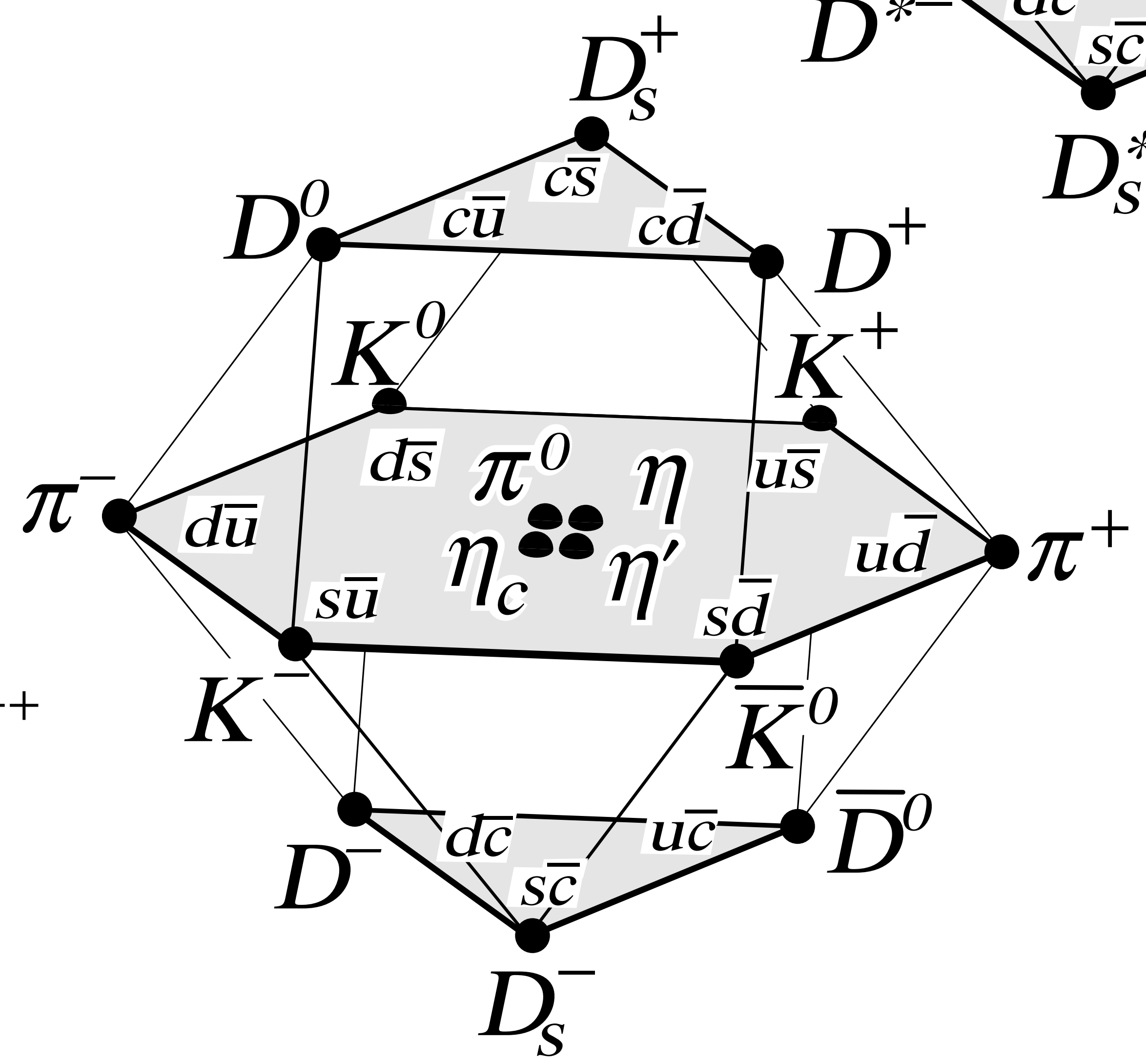




Eight-fold Way:
Account for every
hadron we found so far







“Static” Quark Model

Quarks: spin 1/2 fermions, color charge

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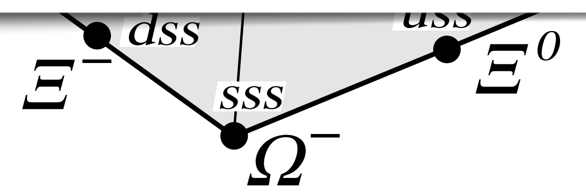
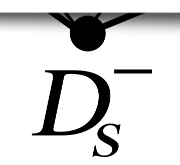
For detailed properties of multi-quark systems the static (constituent) model has failed almost completely and given no predictions which have been verified by experiment.

How can a model be so successful in the quark-antiquark and three quark systems and fail for almost everything else?

What’s missing?

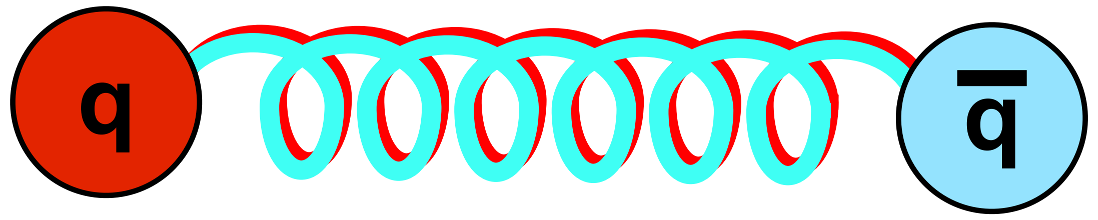


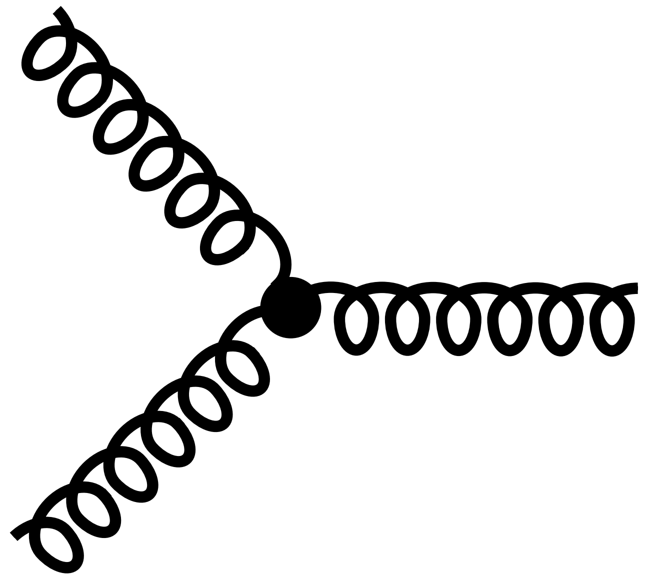


Quantum ChromoDynamics (QCD)

Quantum Chromo Dynamics (QCD) is the fundamental theory of the strong interactions

- 3 (color) charges: **red green blue**
- Matter consist of quarks that carry color charge
- Field quanta: gluons
- Exchange of gluons binds quarks together
- Gluons carry colors $\Rightarrow$ self interact





- Gluons were initially only a conjecture!

Quantum ChromoDynamics (QCD)

Quan … of the

stron

Would George Lucas have been a physicist he would have called the light-sabers **gluon**-sabers

- 3
- M
- F
- E
- G

- G

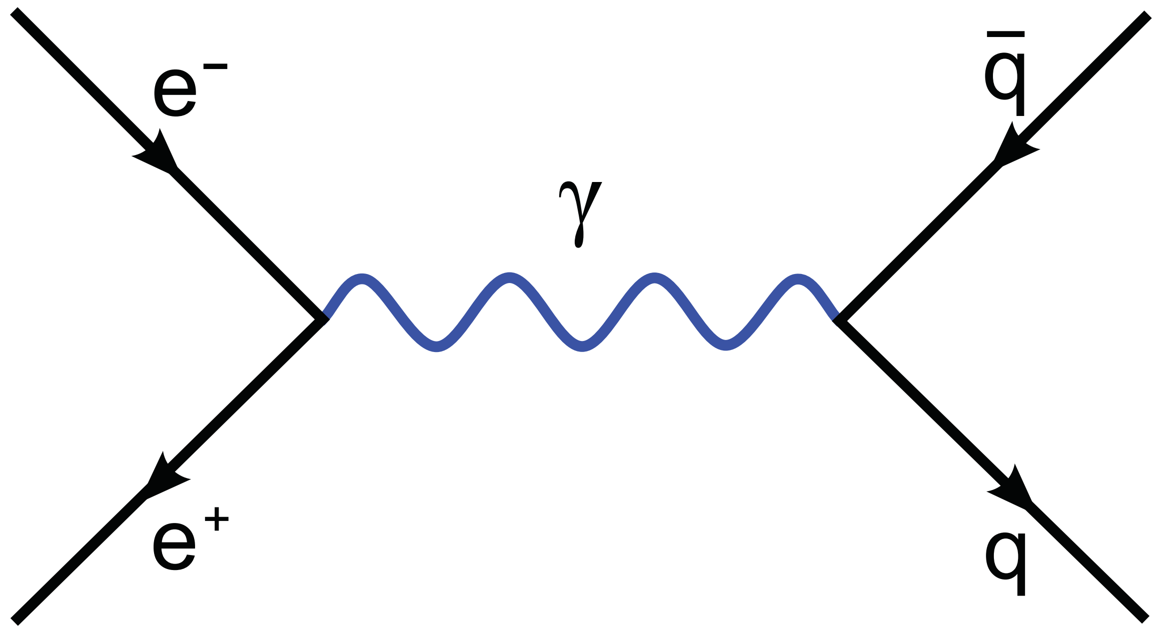
Gluons: They Exist!

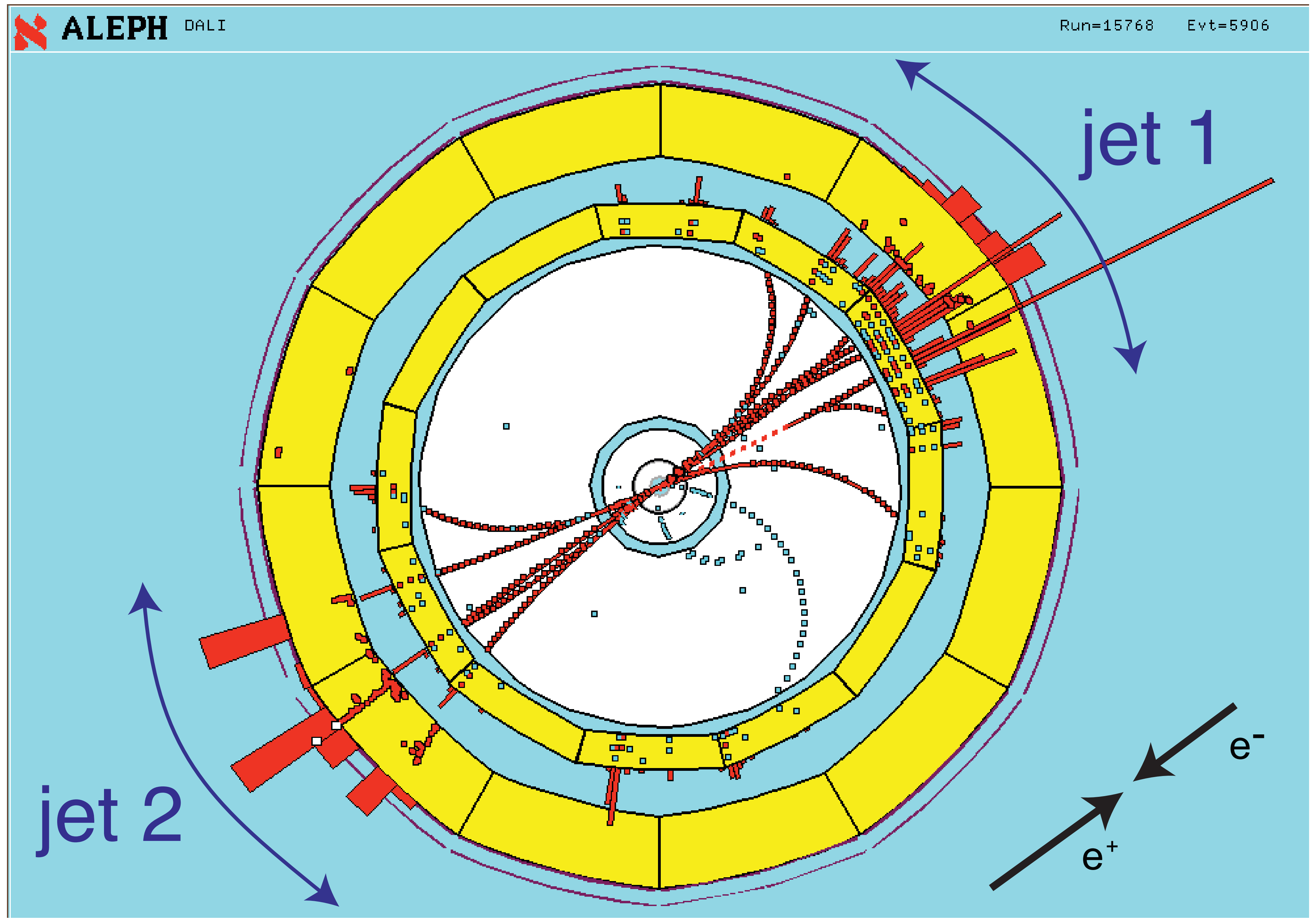
Physics Letters B, 15 December 1980

1979 Discovery of the Gluon

Mark-J, Tasso, Pluto, Jade experiment at PETRA (e^+e^- collider) at DESY ($\sqrt{s}$ = 13 - 32 GeV)

- $e^+ e^- \rightarrow q\ \bar{q} \rightarrow$ 2-jets





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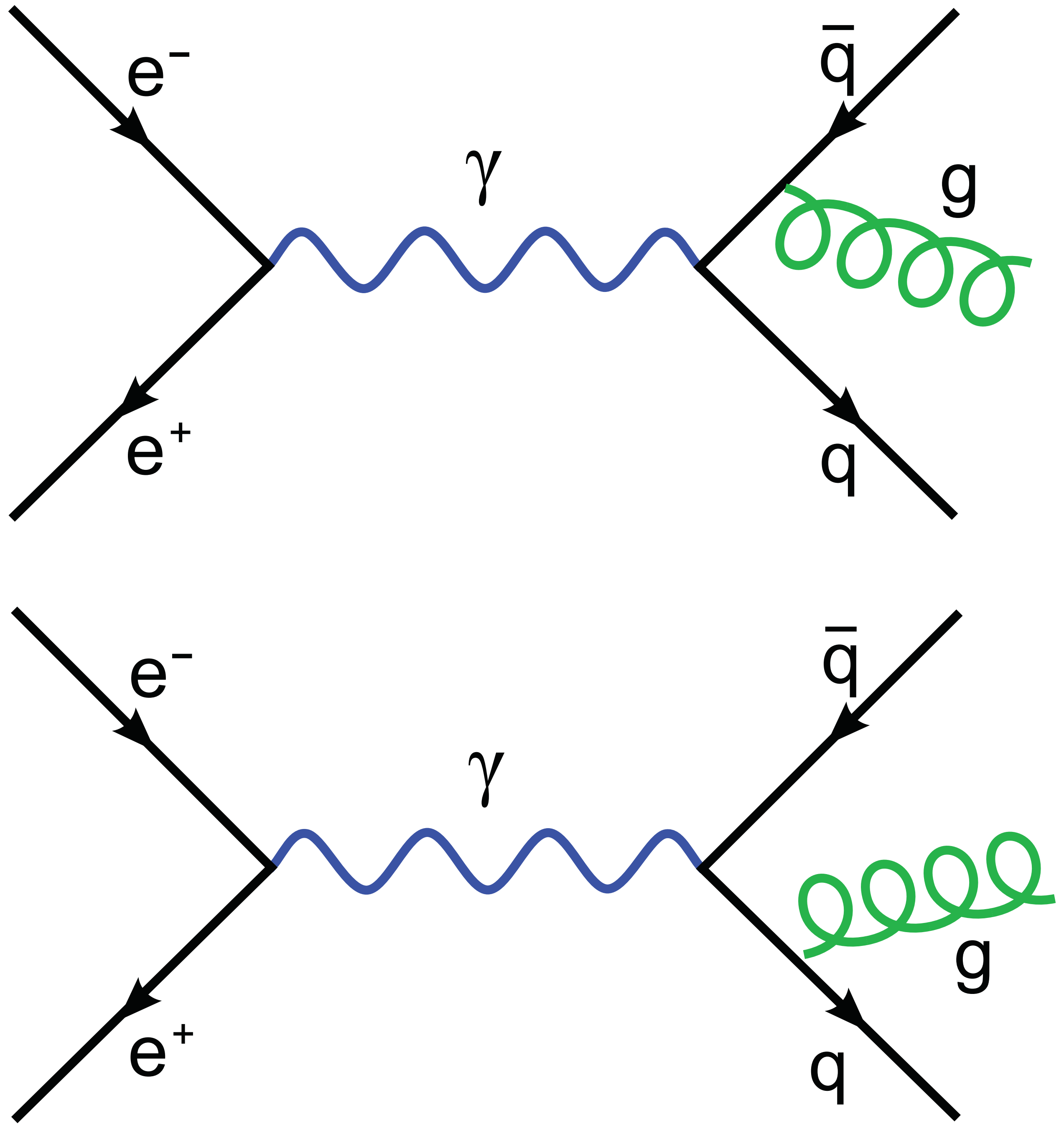

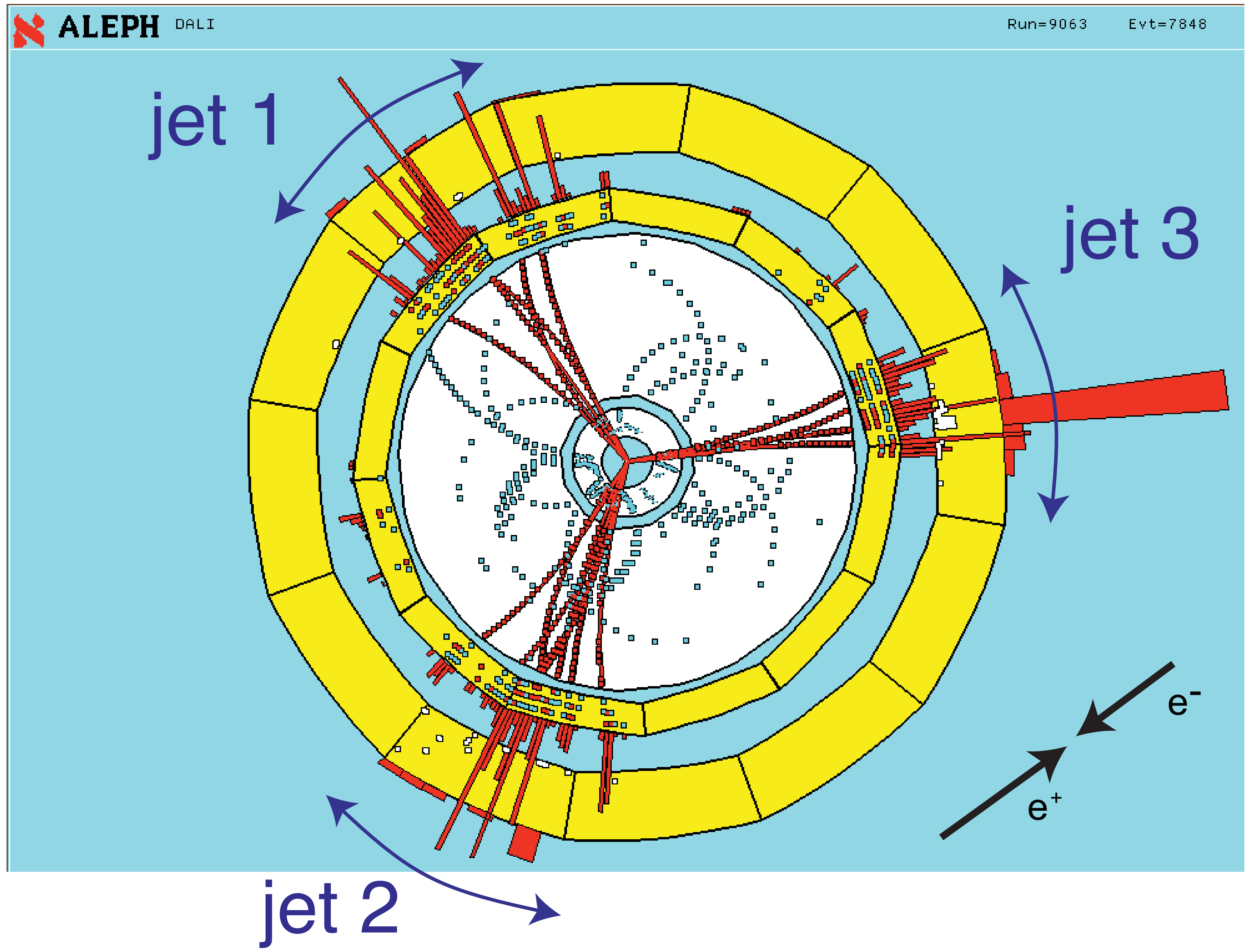

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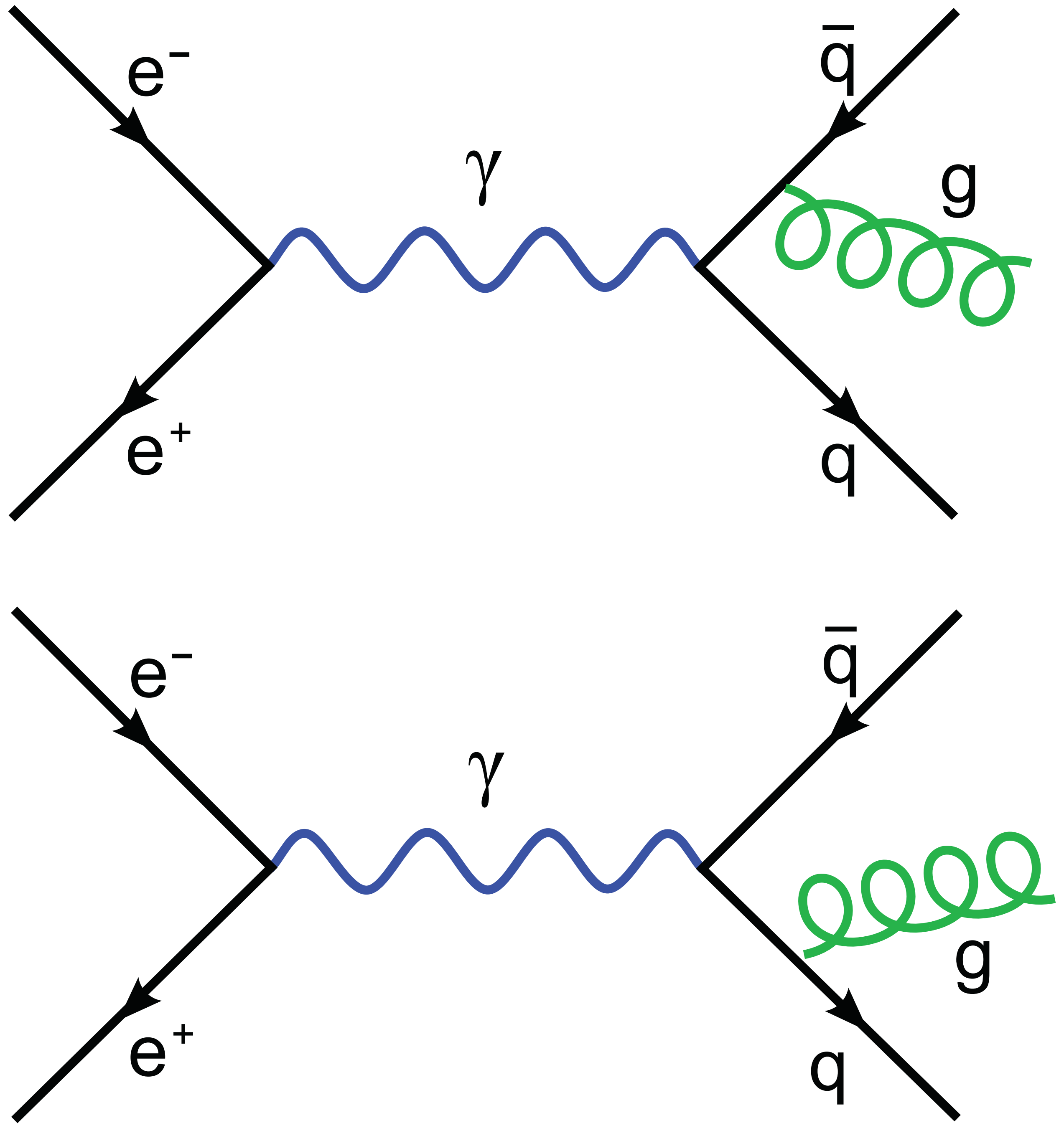
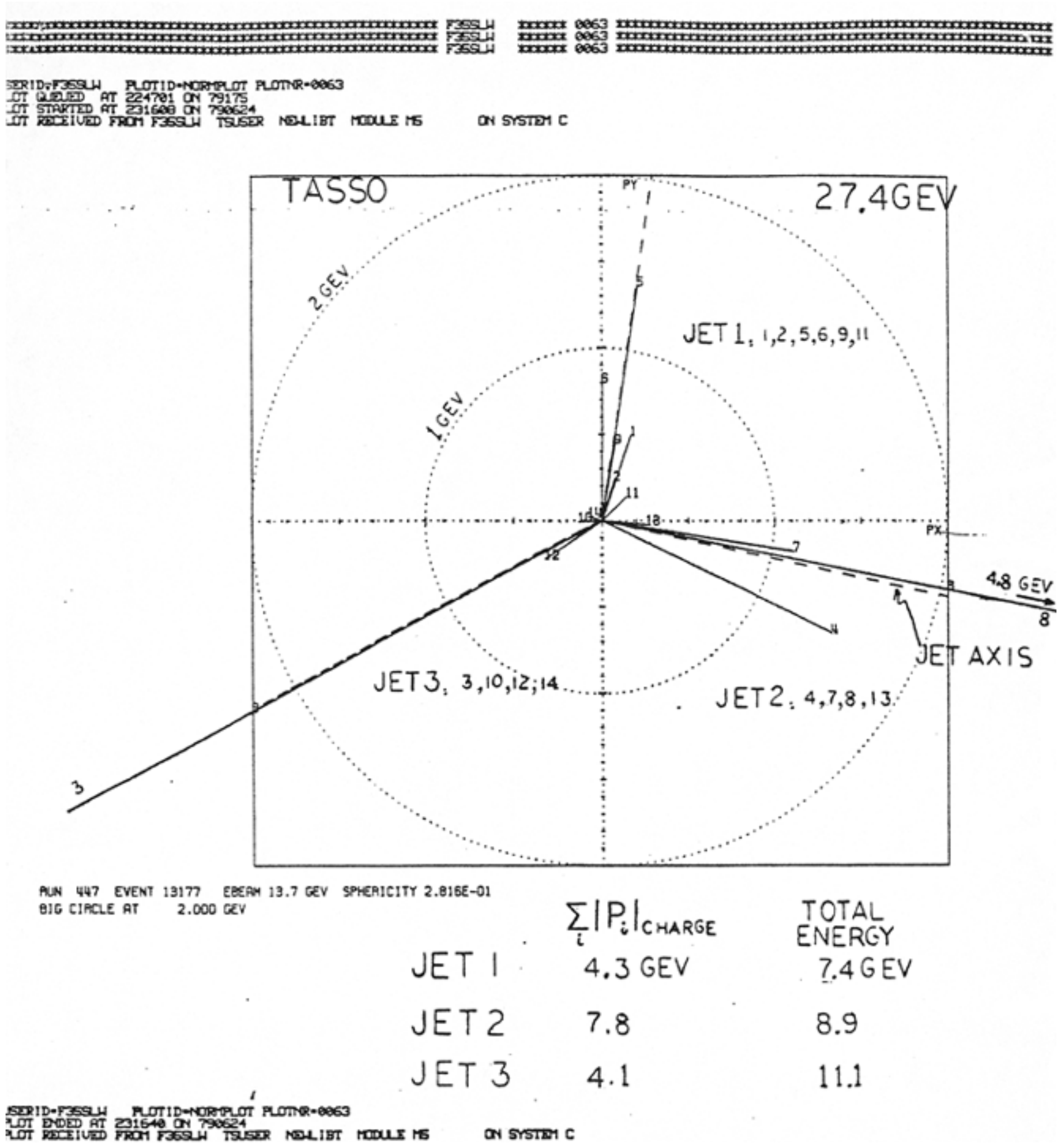




Gluons in QCD - Emergent Phenomena

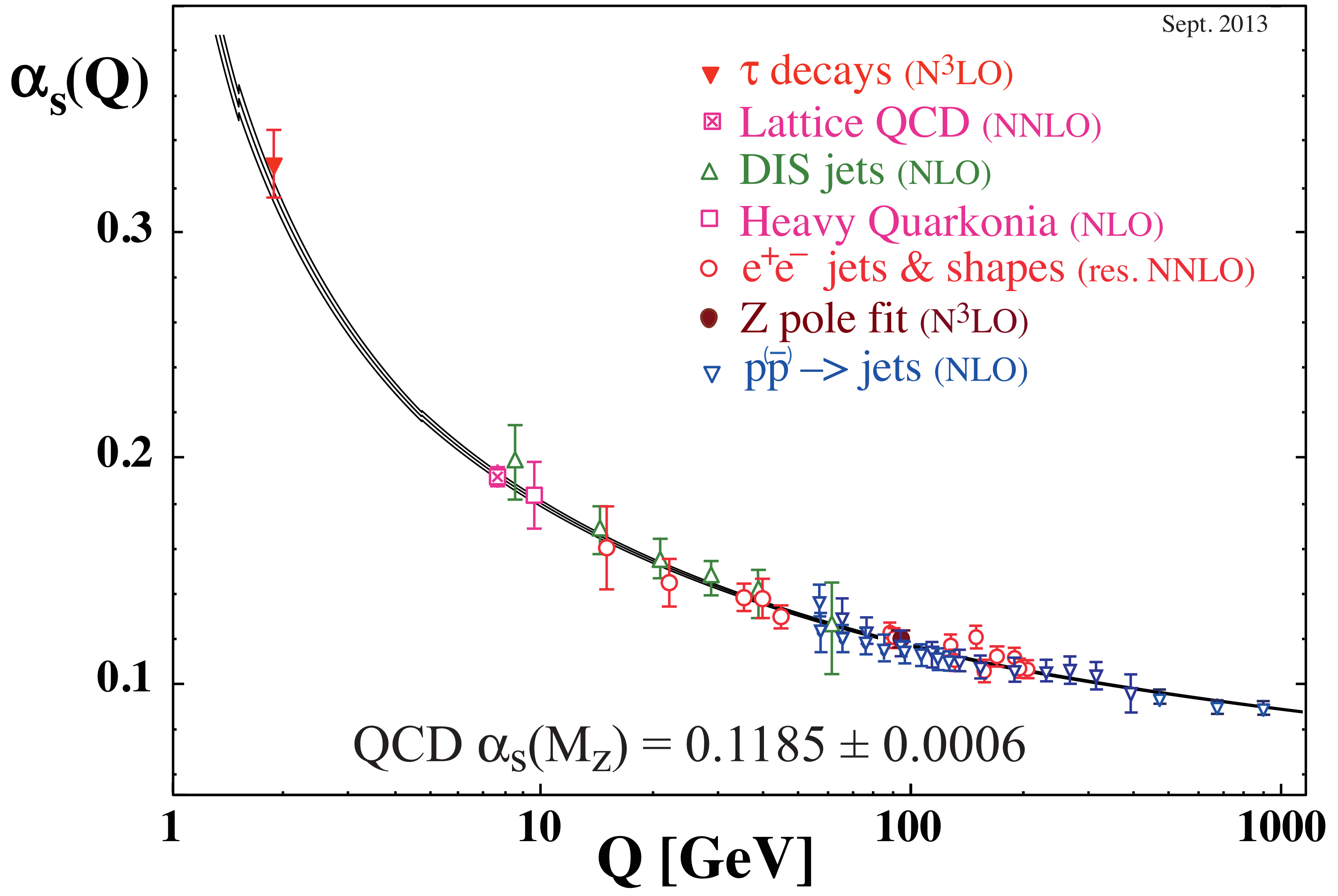
$$L_{QCD} = \bar{q}(i\gamma^\mu \partial_\mu - m)q - g(\bar{q}\gamma^\mu T_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

- “Emergent” Phenomena not evident from Lagrangian
  - Asymptotic Freedom
    - $\alpha_s(Q^2) \sim 1 / \log(Q^2/\Lambda^2)$
    - due to self-interaction of gluons
  - Confinement
    - Free quarks not observed in nature
    - Quarks only in bound states

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

~1/r at short range

long range ~ r



distance

2004, Gross, Politzer, Wilczek

The Essential Mystery

There is an elegance and simplicity to nature's strongest force we do not understand

- (Nearly) all visible matter is made up of quarks and gluons
- But quarks and gluons are not visible
- All strongly interacting matter is an *emergent* consequence of many-body quark-gluon dynamics.

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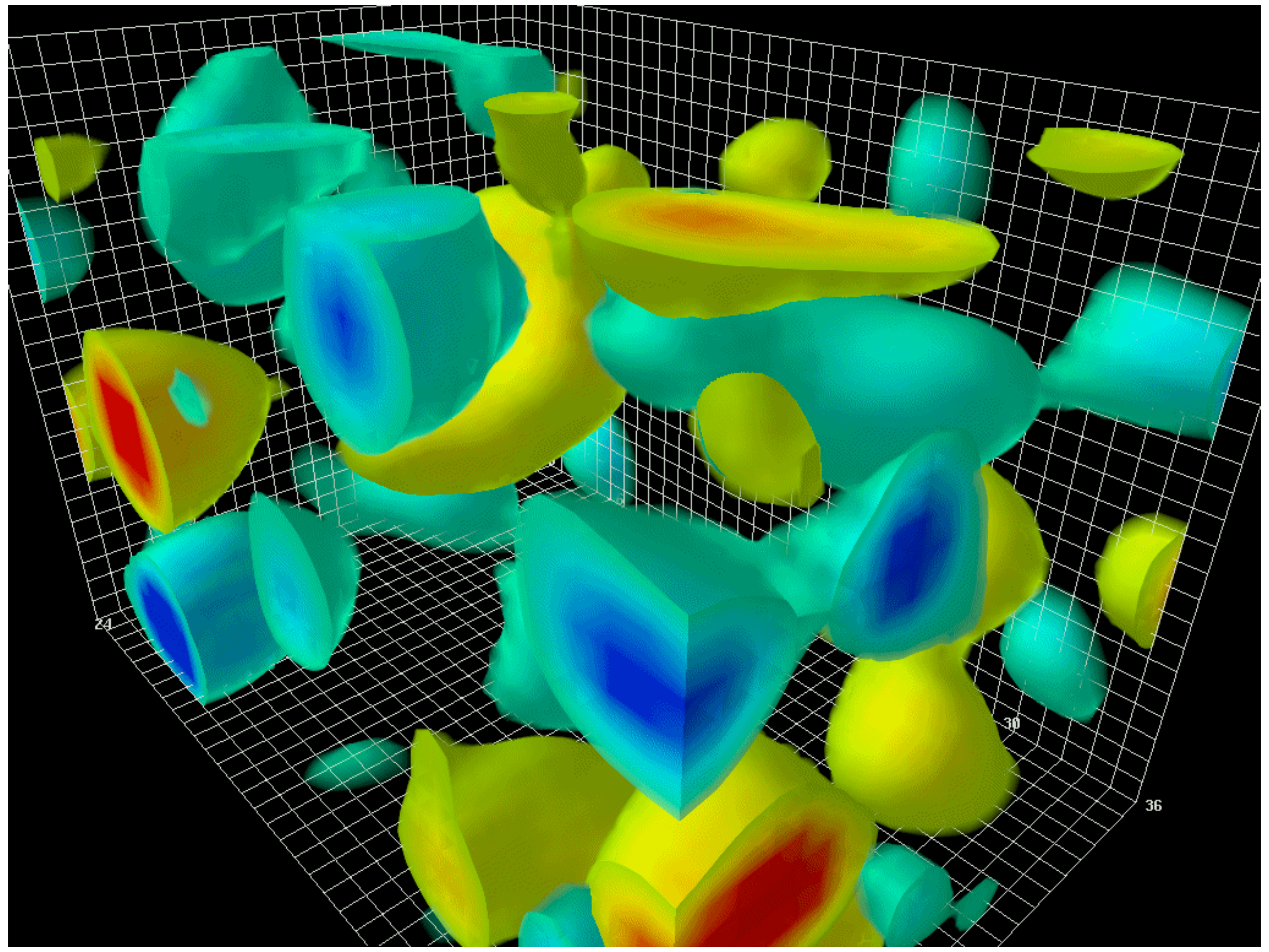
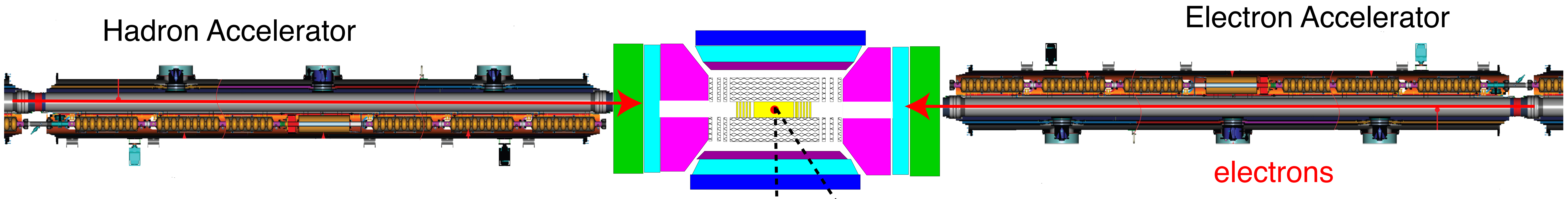
Understanding the origins of matter demands we develop a deep and varied knowledge of this emergent dynamics

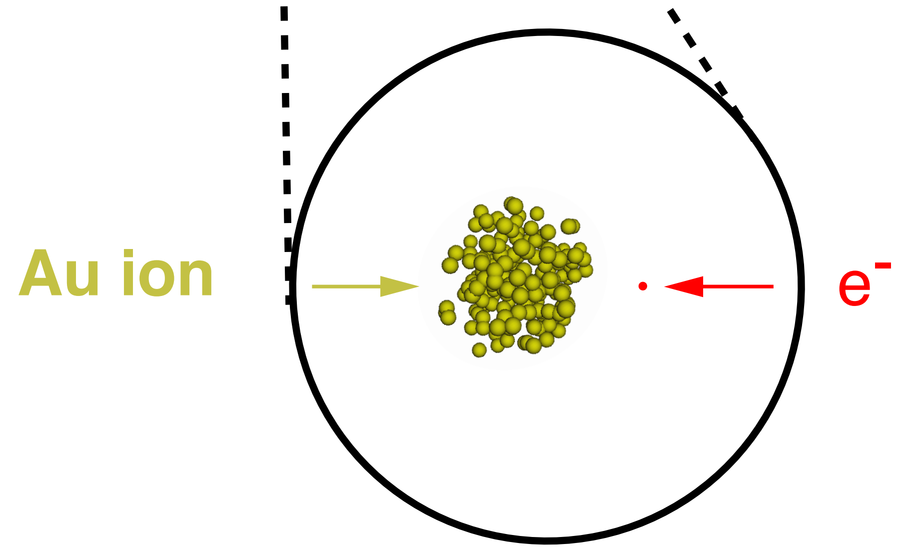


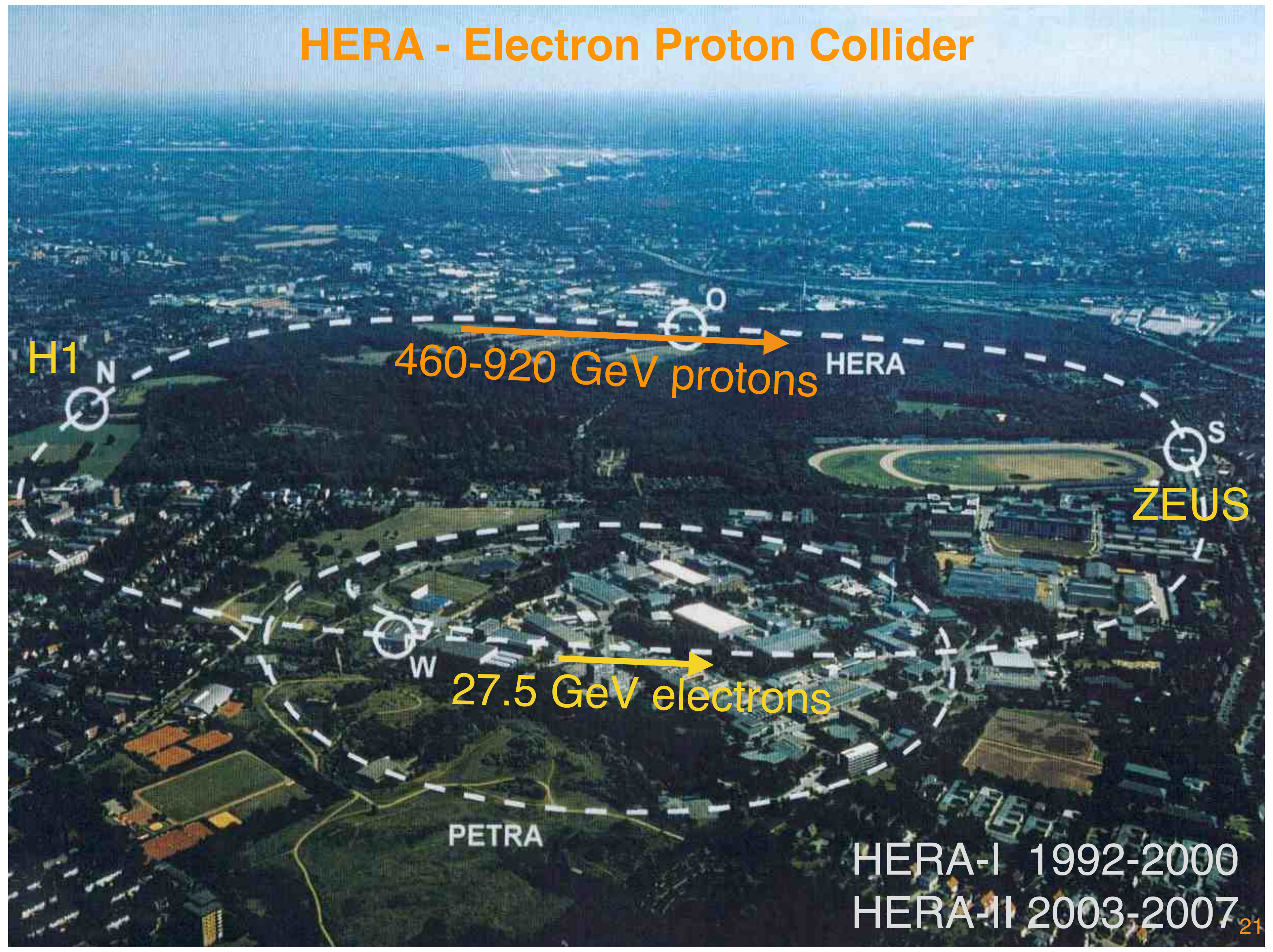
2.Kinematics & Structure Functions

Studying Matter at the Smallest Scales

ep/eA Collider Experiments
Wave Length: 0.0001 fm (10 GeV + 100 GeV)
Resolution: ~ 0.01-0.001 fm

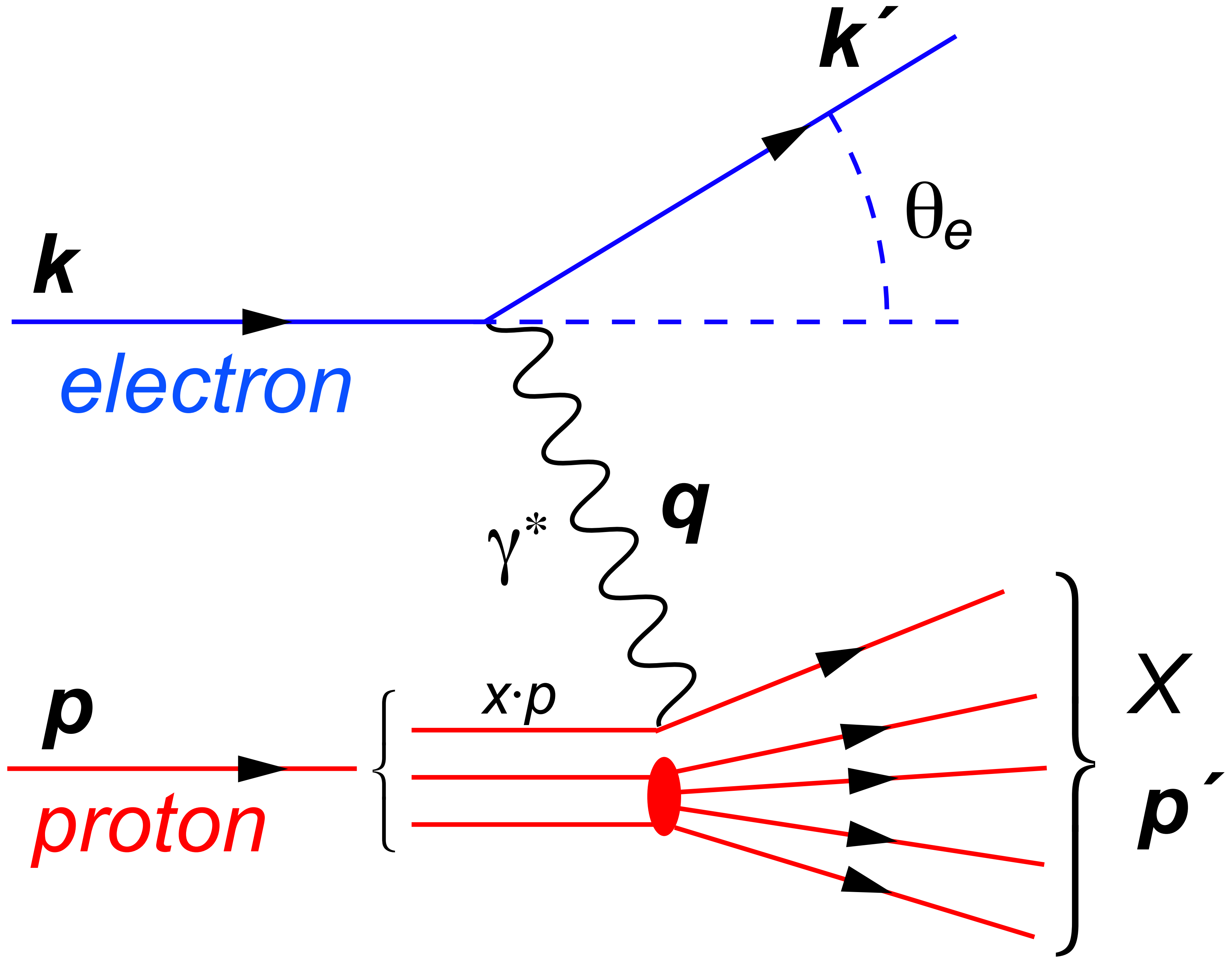






Past: HERA,
Future: EIC, LHeC, …

Deep Inelastic Scattering (DIS)

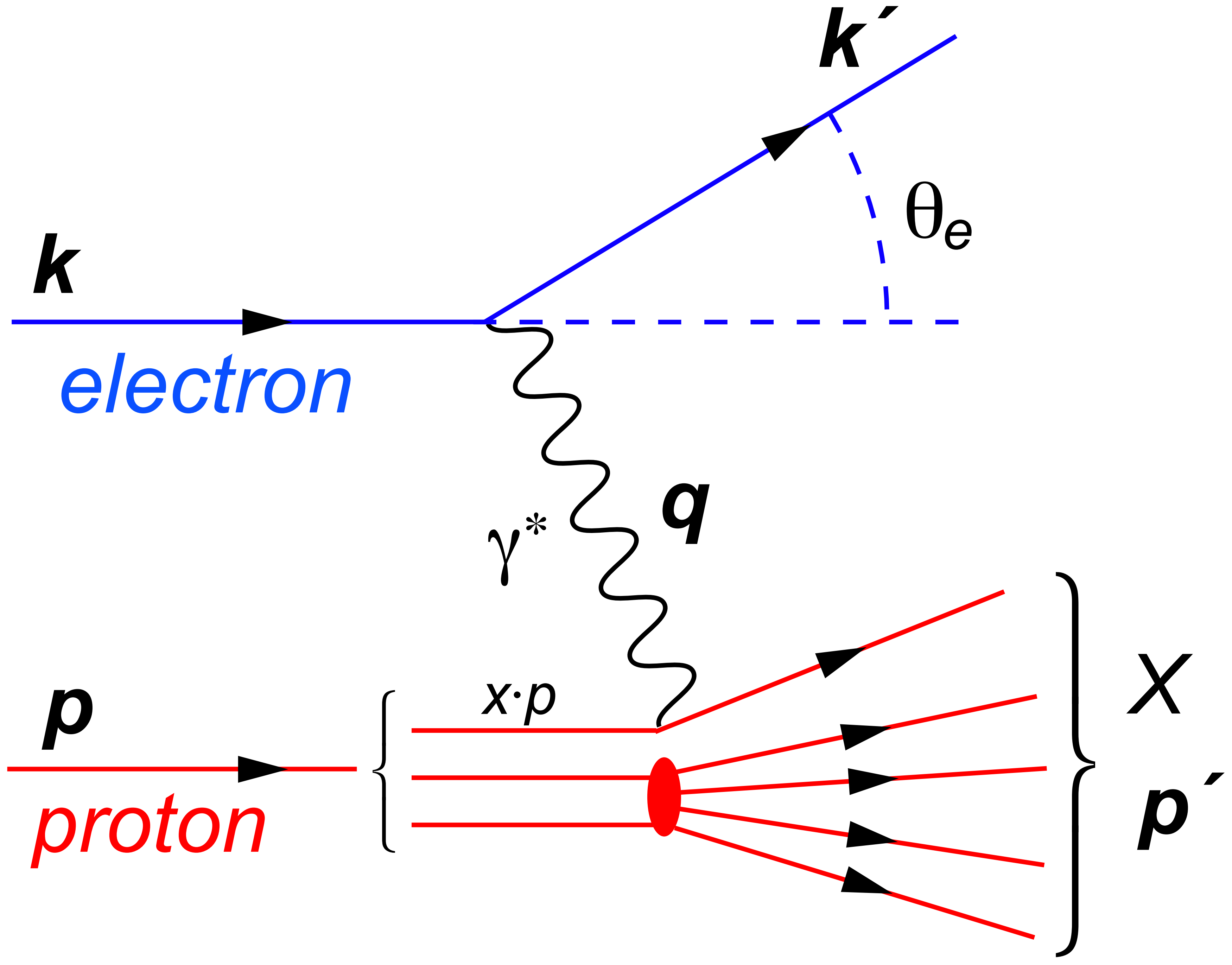


s:

$$s = (k+p)^2 \approx 4E_eE_p$$

- square of center-of-mass energy of electron-hadron system

Deep Inelastic Scattering (DIS)

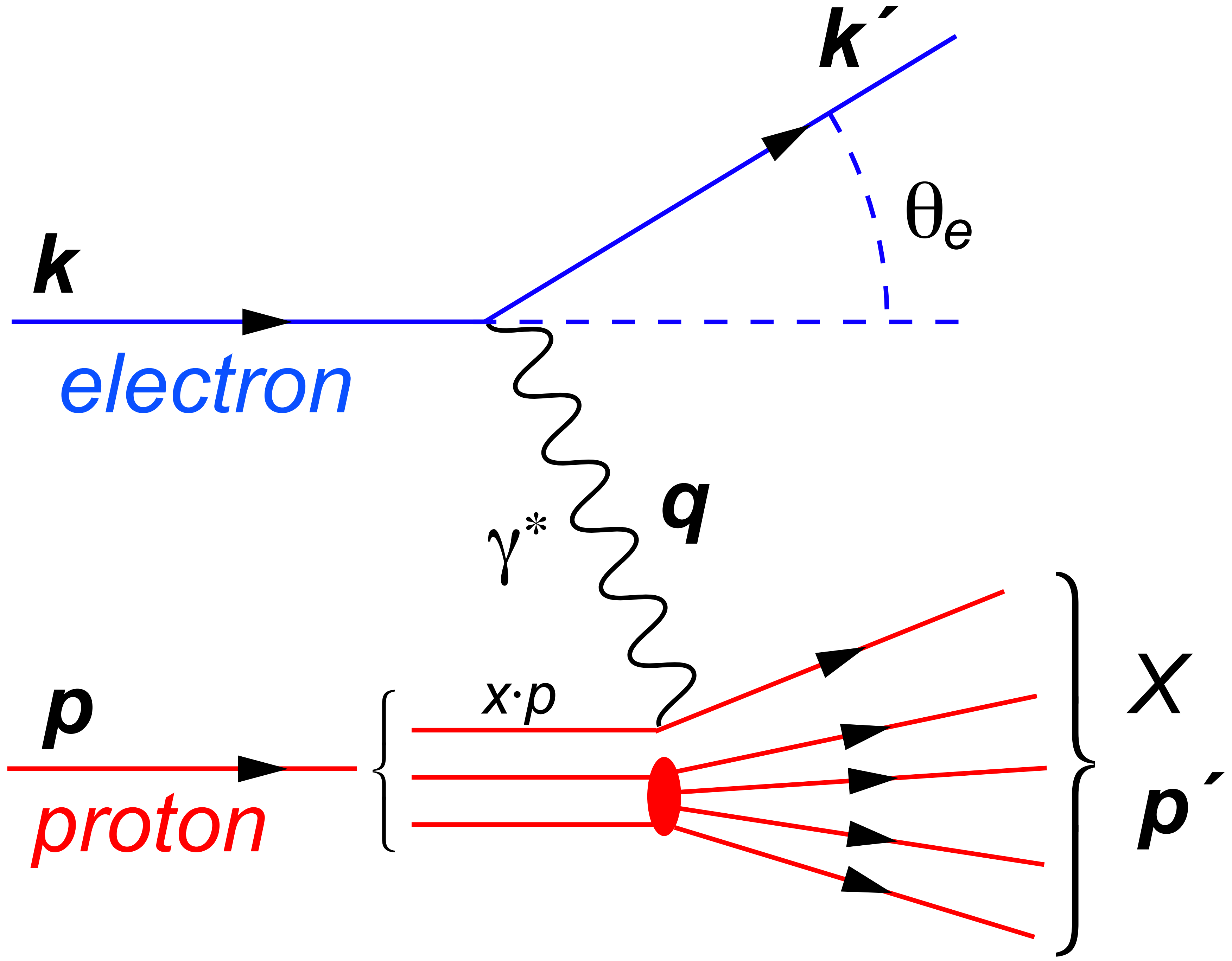


Q2:

$$
\begin{aligned}
Q^2 &= -q^2 = -(k-k')^2 \\
&\approx 4EE'\sin^2\left(\frac{\theta}{2}\right)
\end{aligned}
$$

- 4-momentum transfer from scattered electron
- invariant mass sq. of γ*
- “Resolution” power
- Virtuality
  - real photon Q = 0

Deep Inelastic Scattering (DIS)

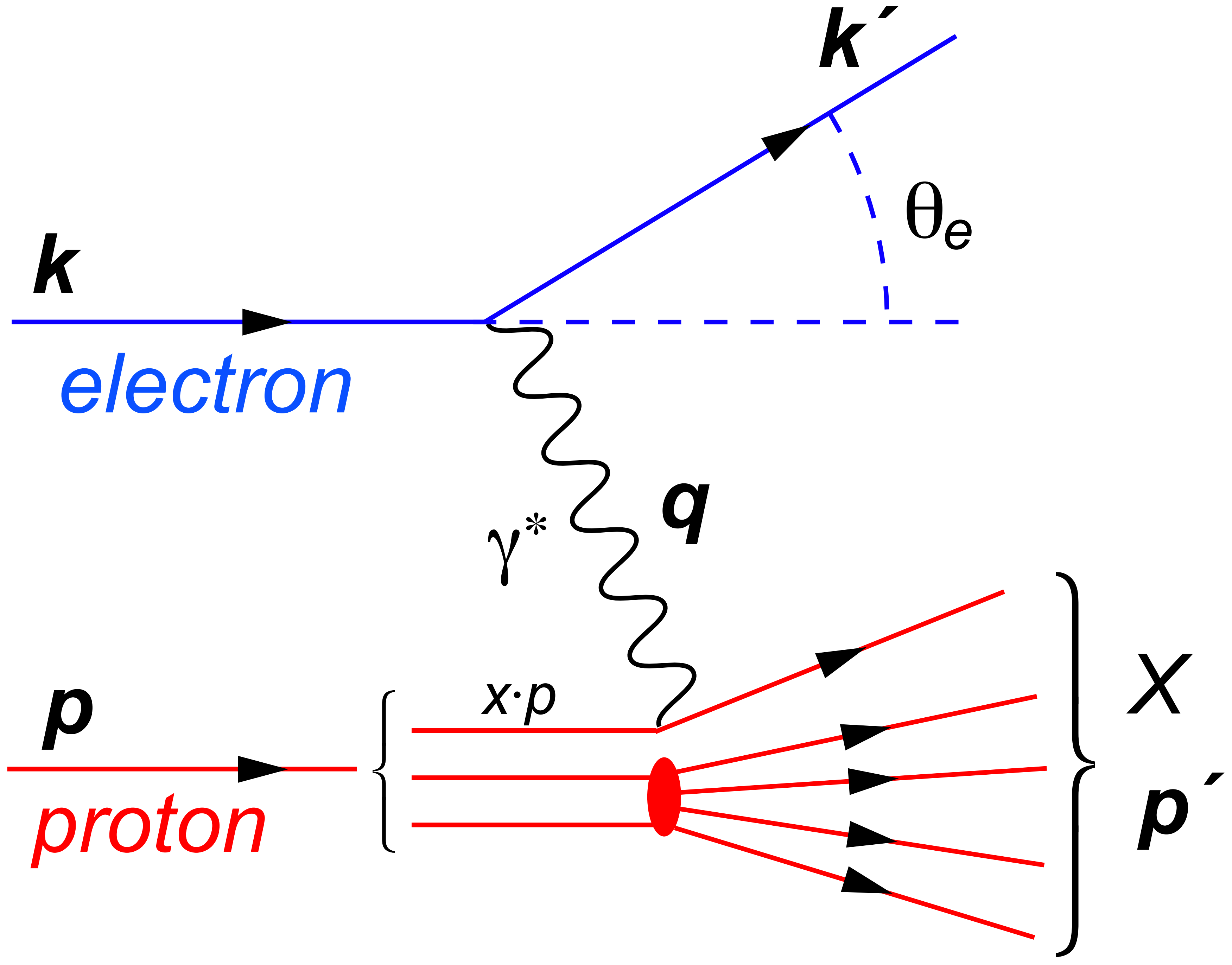


y:

$$y = \frac{pq}{pk} = 1 - \frac{E_e'}{E_e}\cos^2\left(\frac{\theta_e'}{2}\right)$$

- Inelasticity
- Fraction of electron's energy lost in nucleon restframe
- $0 < y < 1$

Deep Inelastic Scattering (DIS)

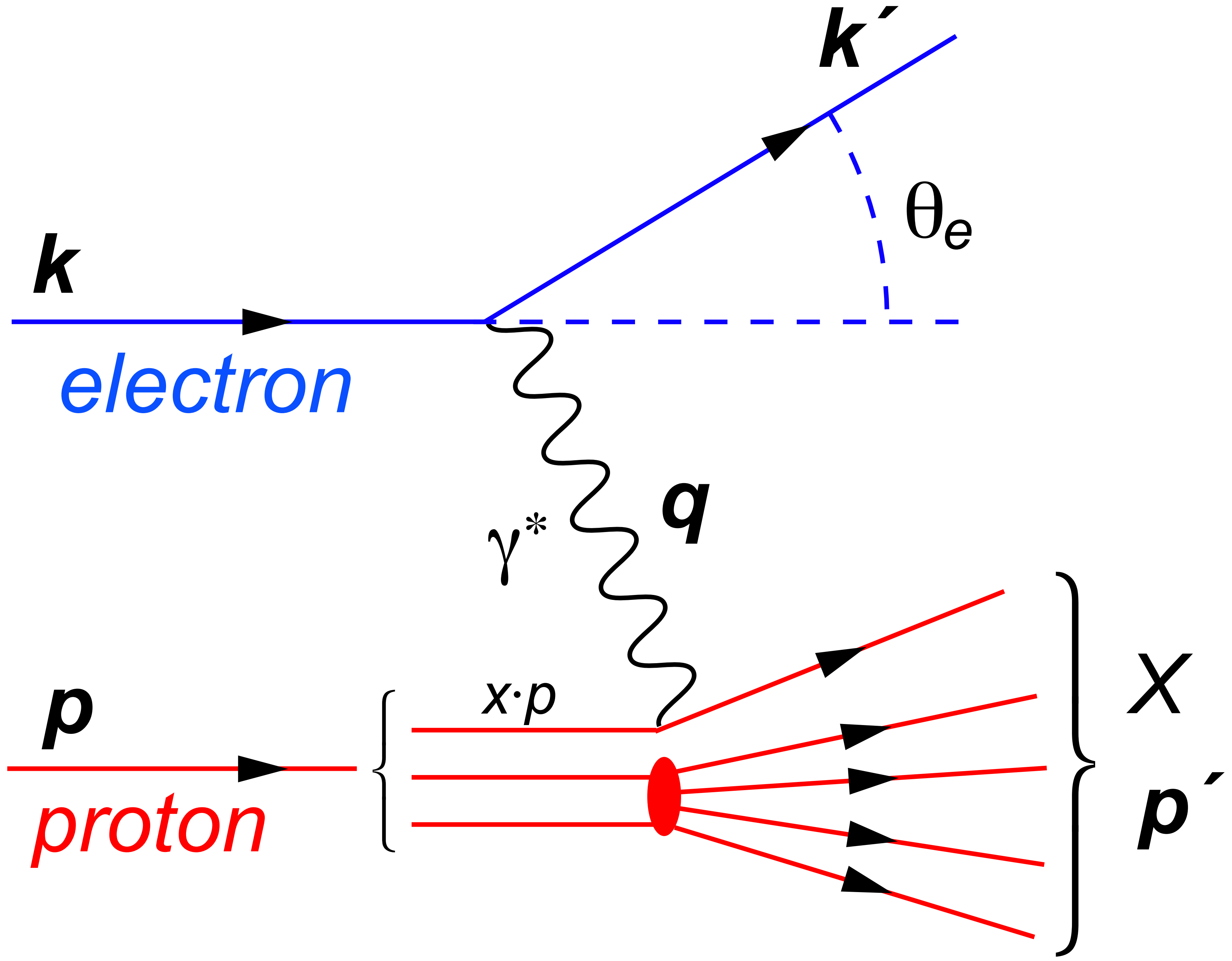


x:

$$x = \frac{Q^2}{2pq}$$

- Bjorken-x
- x is fraction of the nucleon’s momentum carried by the struck quark

Deep Inelastic Scattering (DIS)



x: momentum fraction of parton

Q^2: resolution power

y: inelasticity

s: center-of-mass energy sq.

$$Q^2 \approx s \cdot x \cdot y$$

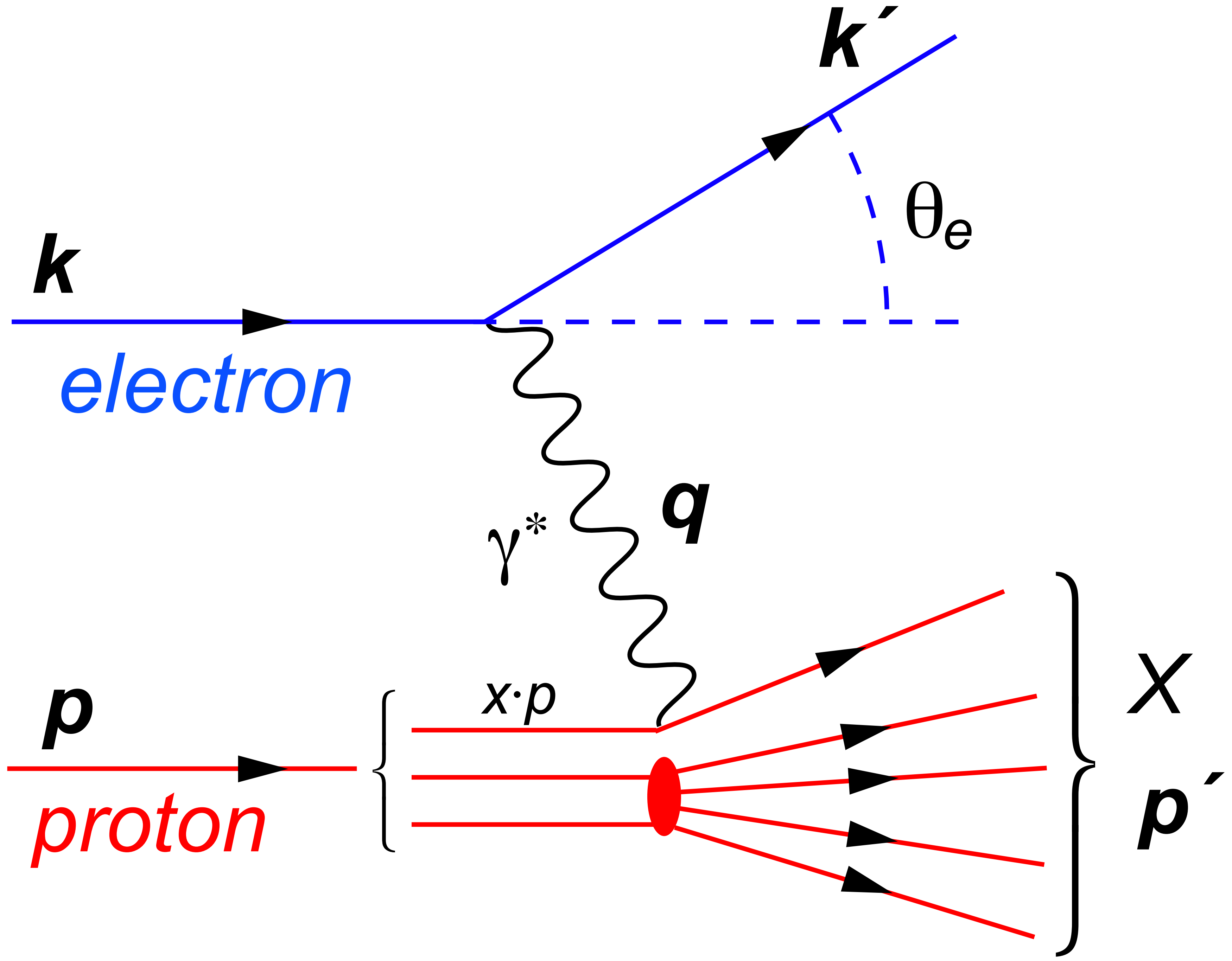
Deep ($Q^2 \gg m_p^2$)

Inelastic ($W^2 \gg m_p^2$)

Scattering = DIS

$W^2 = (p+q)^2$ is the squared invariant mass of the produced hadronic system X

Deep Inelastic Scattering (DIS)



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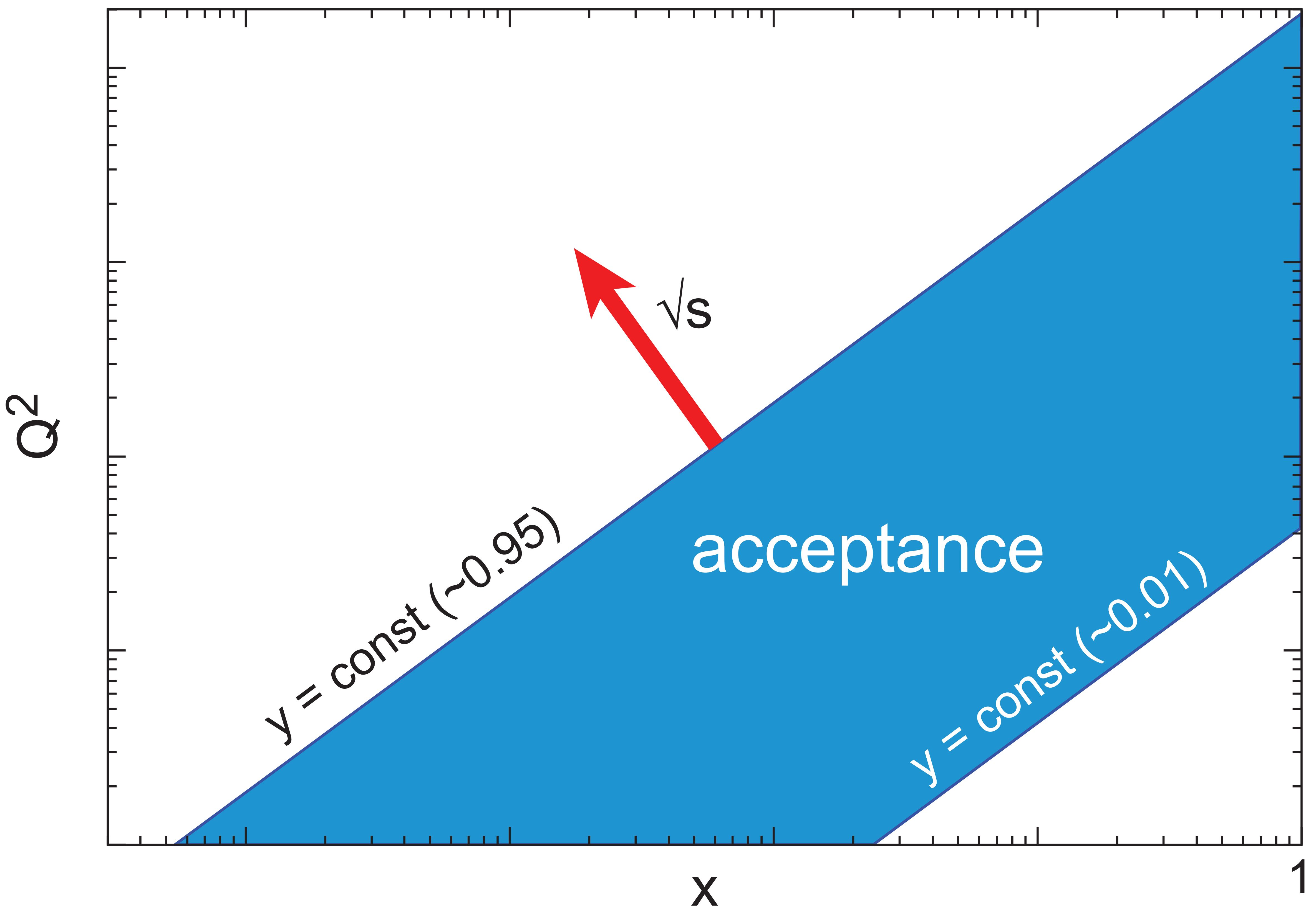
Scattering = DIS

$W^2 = (p+q)^2$ is the squared invariant mass of the produced hadronic system X

N.B.: This picture was developed in the "infinite momentum frame" (IMF). That works nicely when one assume massless quarks and gluons (partons). Despite all this it is also used for example for massive charm quarks. Some care has to be taken and x needs to be "adjusted".

The x-Q^2 Plane



$$Q^2 \approx s \cdot x \cdot y$$

- Low-x reach requires large $\sqrt{s}$
- Large-Q^2 reach requires large $\sqrt{s}$
- *y* at colliders typically limited to approx. 0.01 < y < 0.95
  - y ~ 0: too little energy to be detected
  - y ~ 1: along the beamline

Structure Functions

Inclusive e+p collisions:
(only scattered electron is measured, rest ignored)

F_2 and F_L are key in understanding the structure of hadrons

N.B.: At very high energies a 3rd
structure function comes into play: F_3
Ignored here and in the rest

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(only scattered electron is measured, rest ignored)

$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark momentum distributions

gluon momentum distribution

F_2 and F_L are key in understanding the structure of hadrons

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Ignored here and in the rest

More Practical: Reduced Cross-Section

Inclusive Cross-Section:

$$\frac{d^2\sigma^{eA\to eX}}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

Reduced Cross-Section:

$$\sigma_r = \left(\frac{d^2\sigma}{dx dQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+}F_L^A(x,Q^2)$$ where $Y^+ = 1+(1-y)^2$

More Practical: Reduced Cross-Section

Inclusive Cross-Section:

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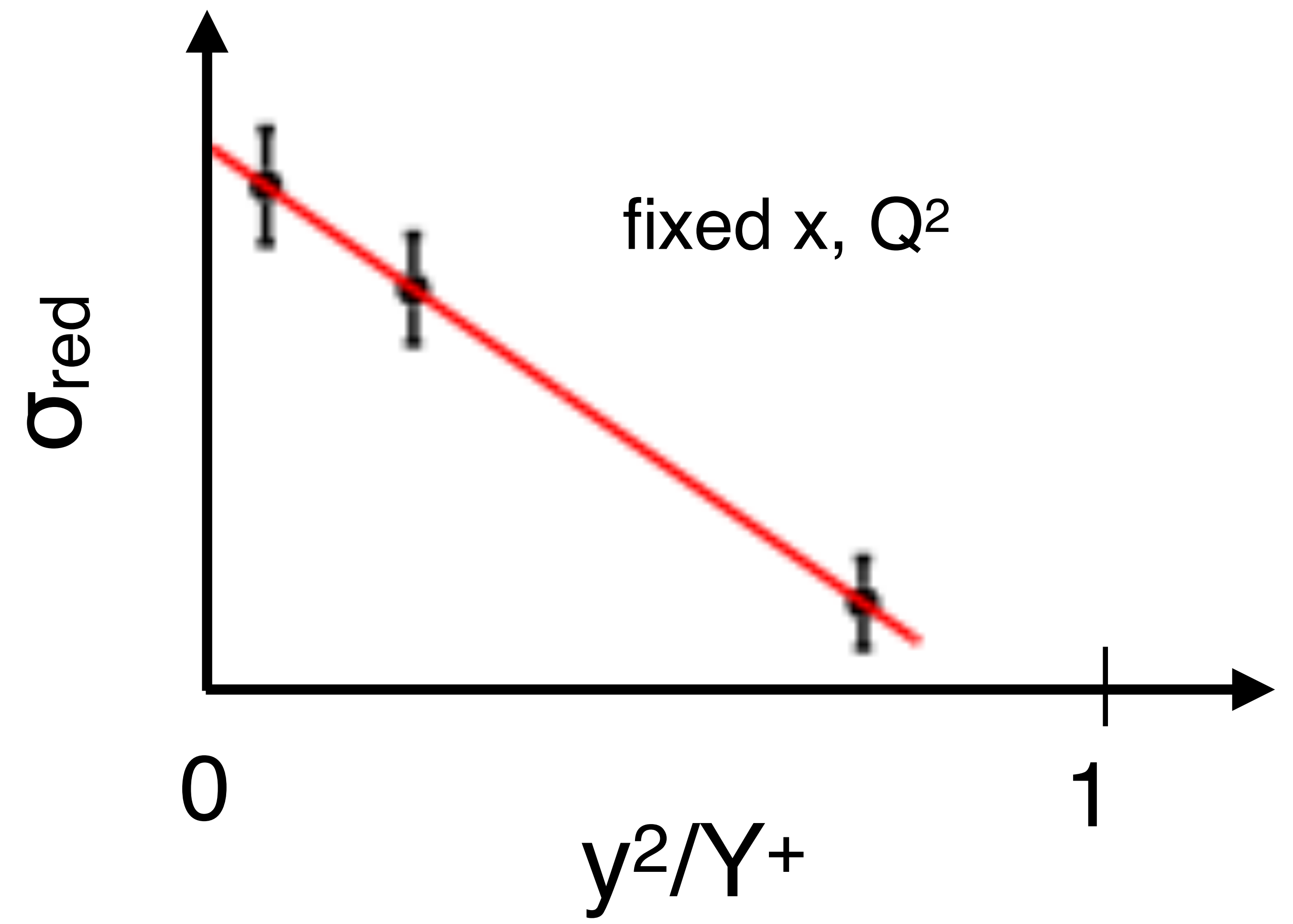
$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+} F_L^A(x,Q^2) \qquad \text{where } Y^+ = 1 + (1-y)^2$$

Rosenbluth Separation:

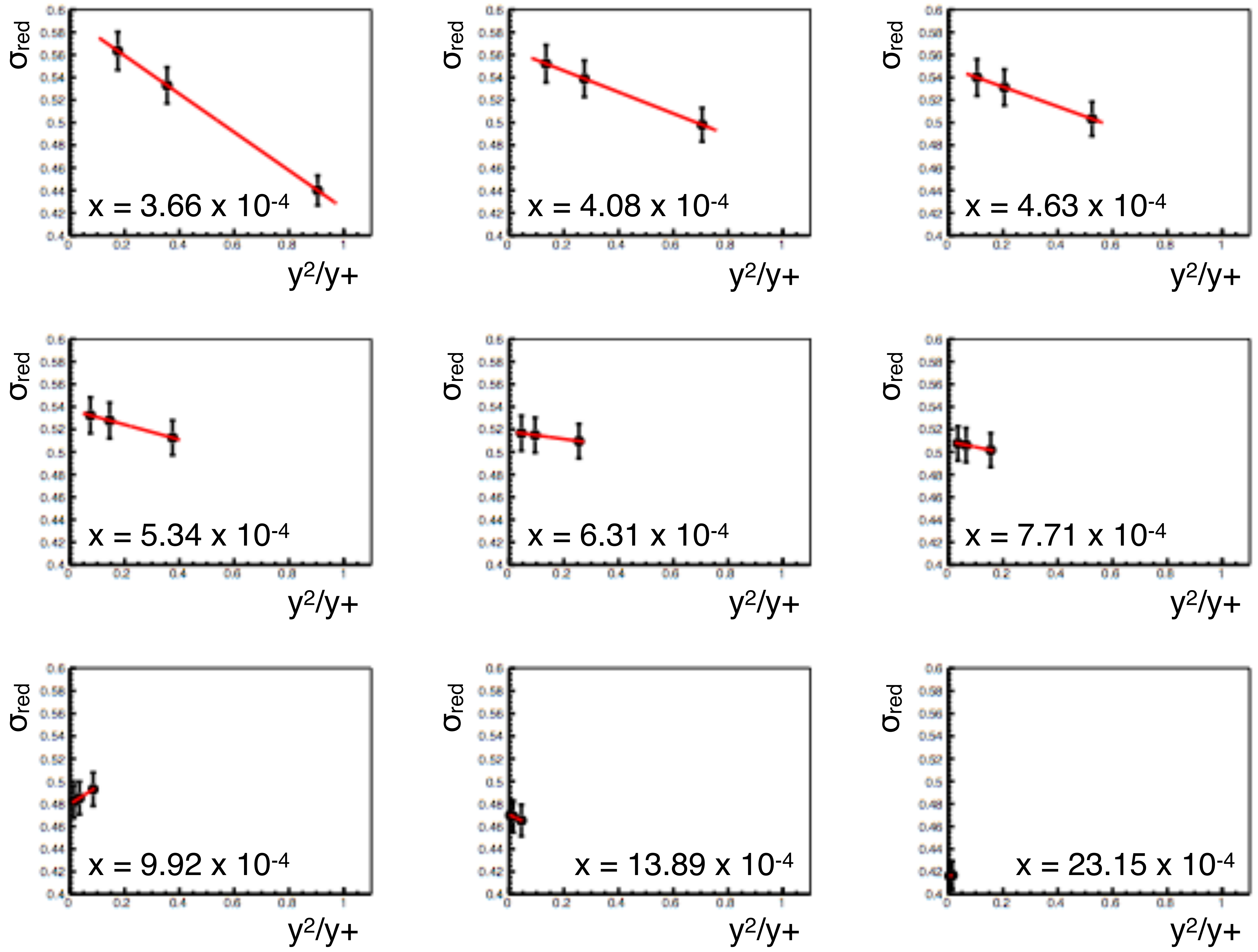
- Recall $Q^2 = x\, y\, s$
- Measure at different $\sqrt{s}$
- Plot σ_{red} versus y^2/Y^+ for fixed x, Q^2
- F_2 is σ_{red} at $y^2/Y^+ = 0$
- F_L = Slope of y^2/Y^+



F_L - Rosenbluth Separation at HERA

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+} F_L^A(x,Q^2)$$

$Q^2 = 1.389\ GeV^2$



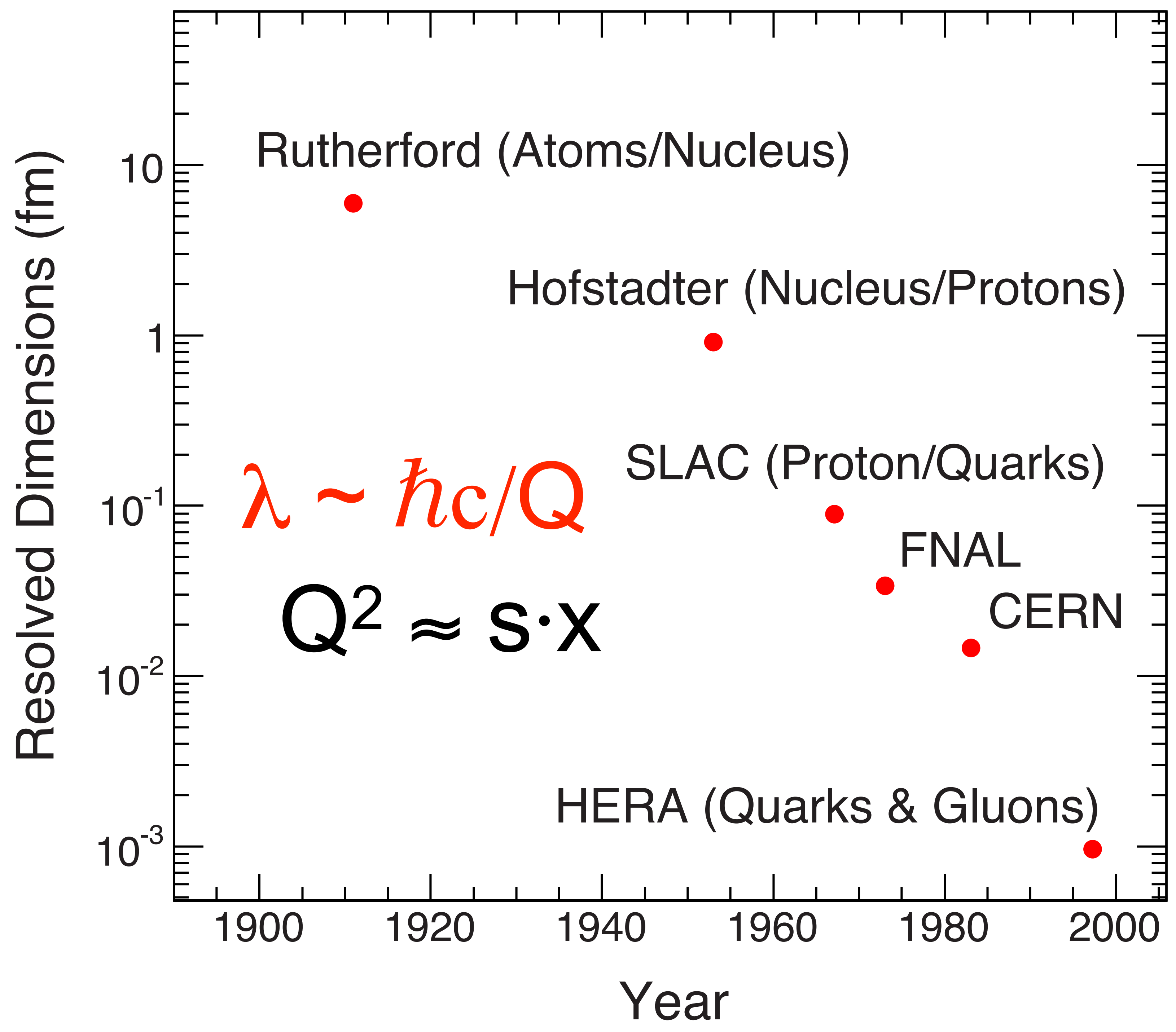
HERA run most of if life time at full energy.
Only in the last year did they vary E_p to measure F_L:

E_p=920 GeV
E_p=820 GeV
E_p=575 GeV
E_p=460 GeV

The measurements are unfortunately not overwhelming

F_2: The Key Structure Function

$$\frac{d^2\sigma^{ep\rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2)$$



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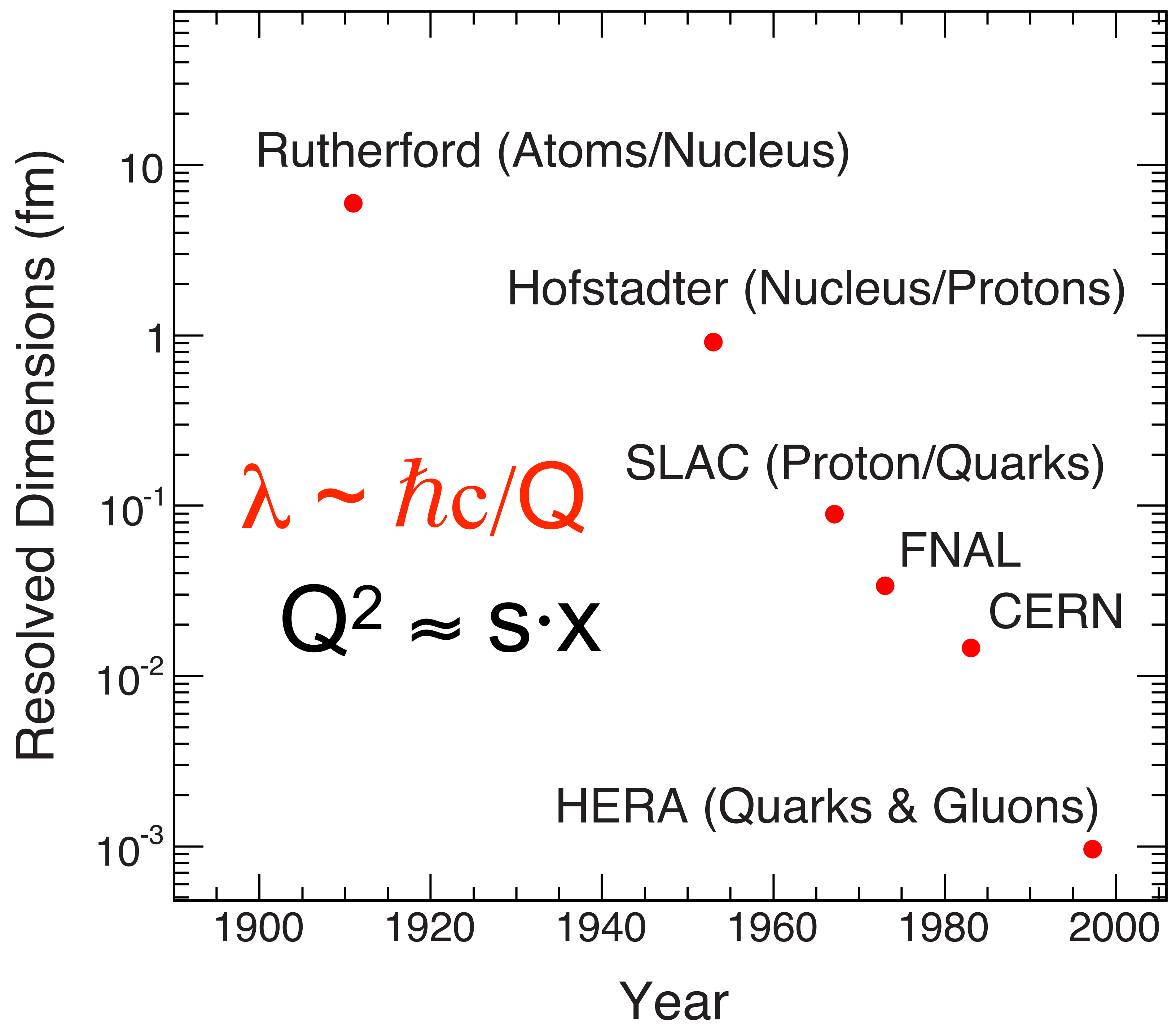

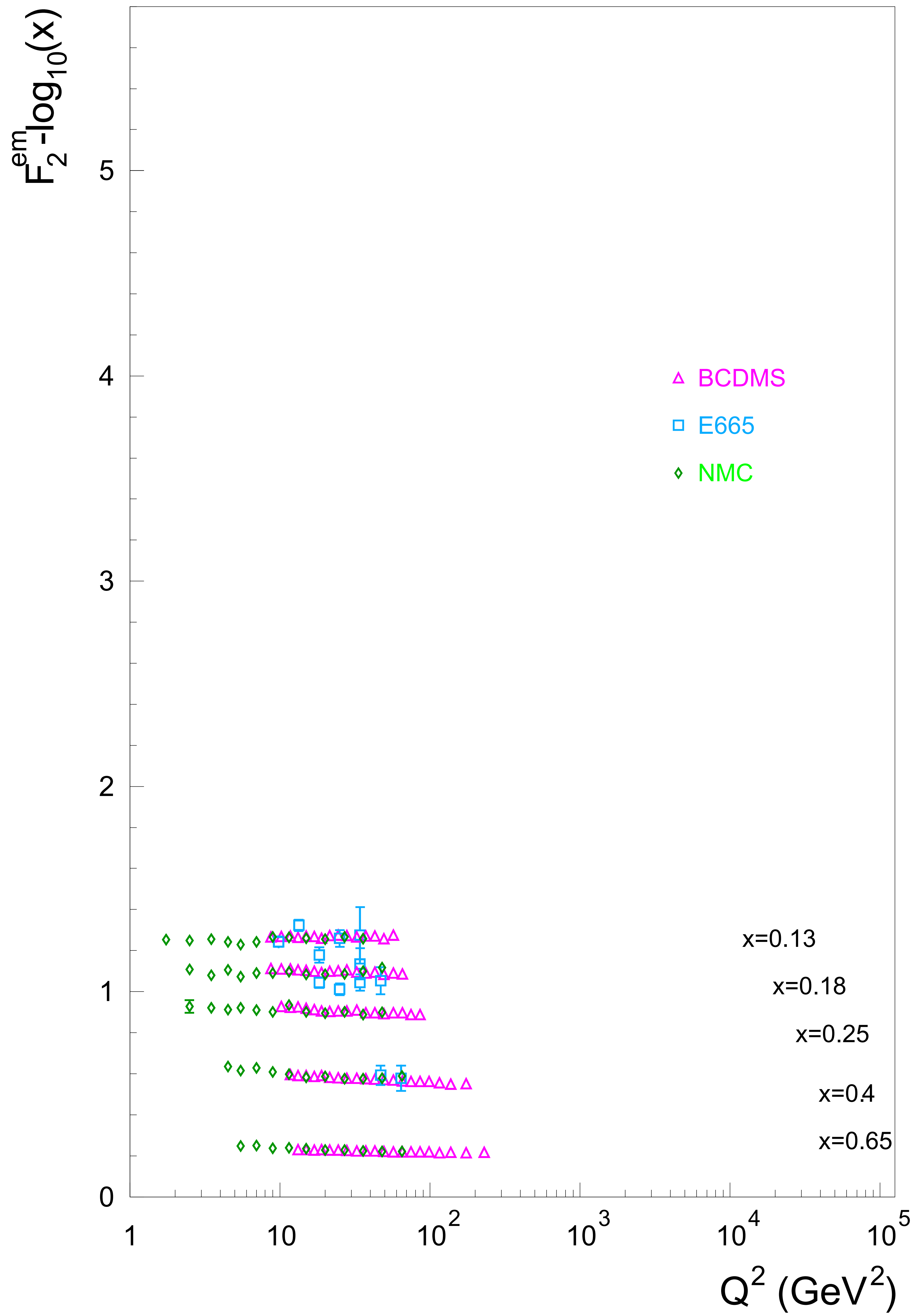

Bjorken Scaling: $F_2(x, Q^2) \rightarrow F_2(x)$

virtual photon interacts with a single essentially free quark

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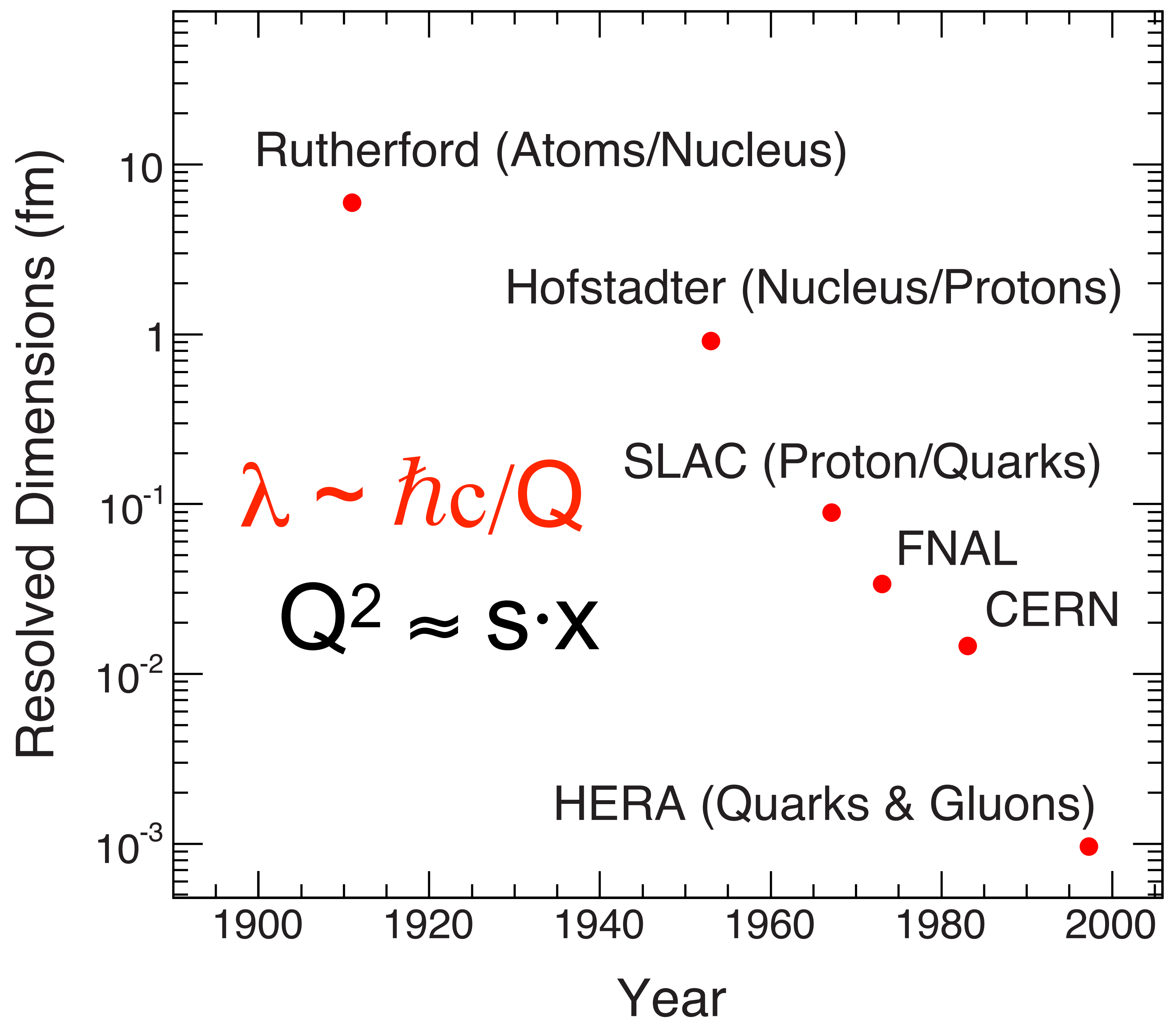

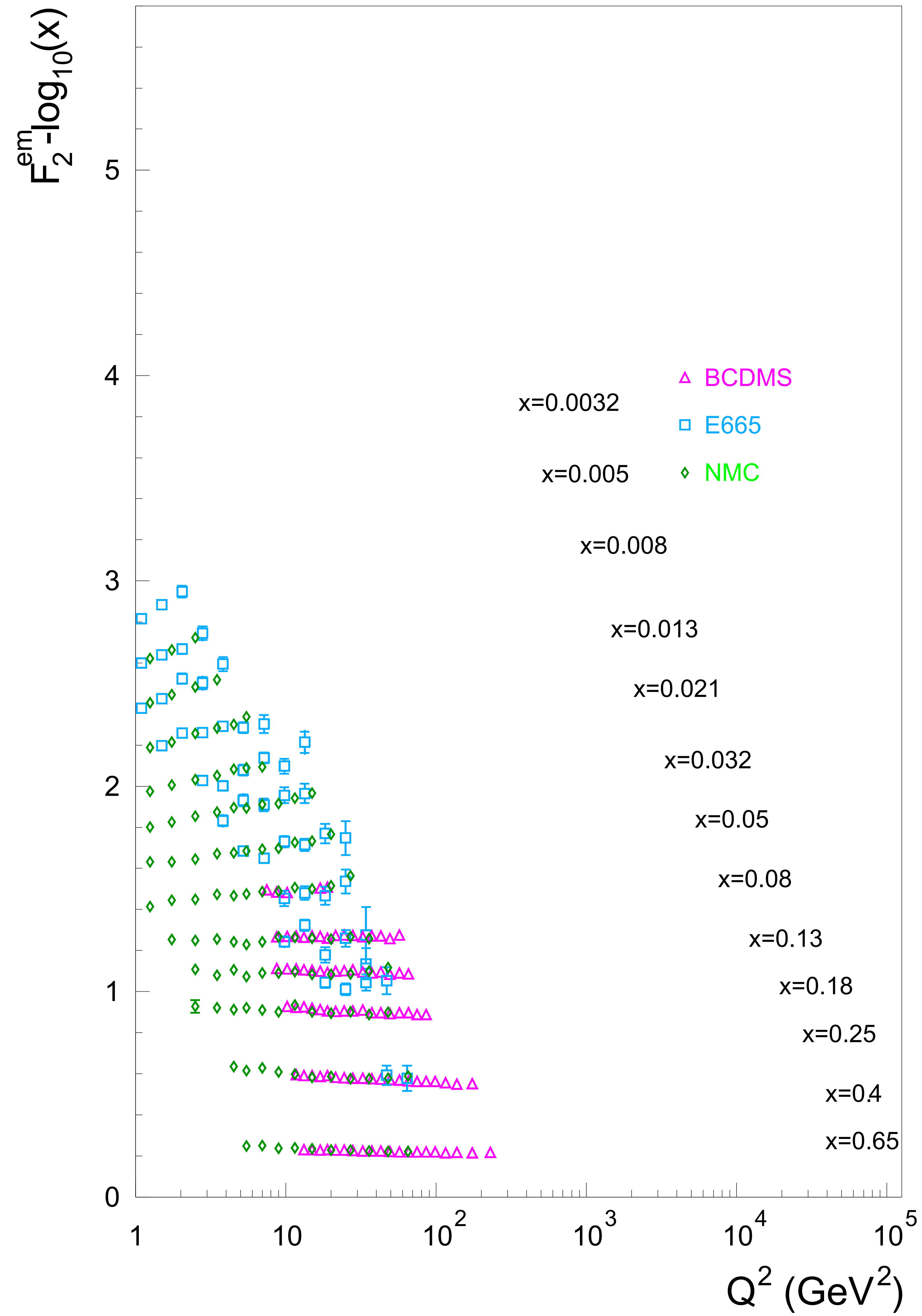

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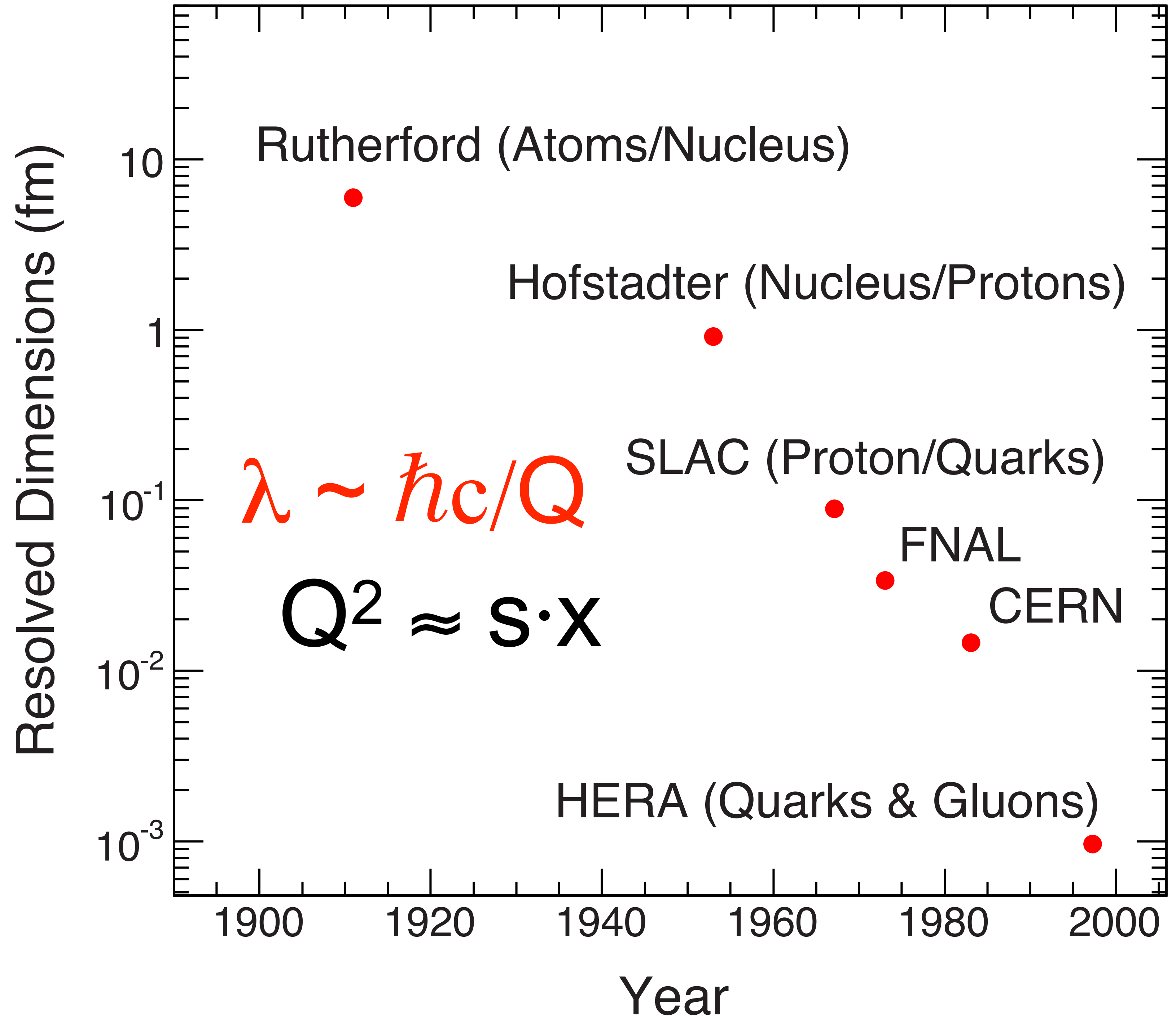

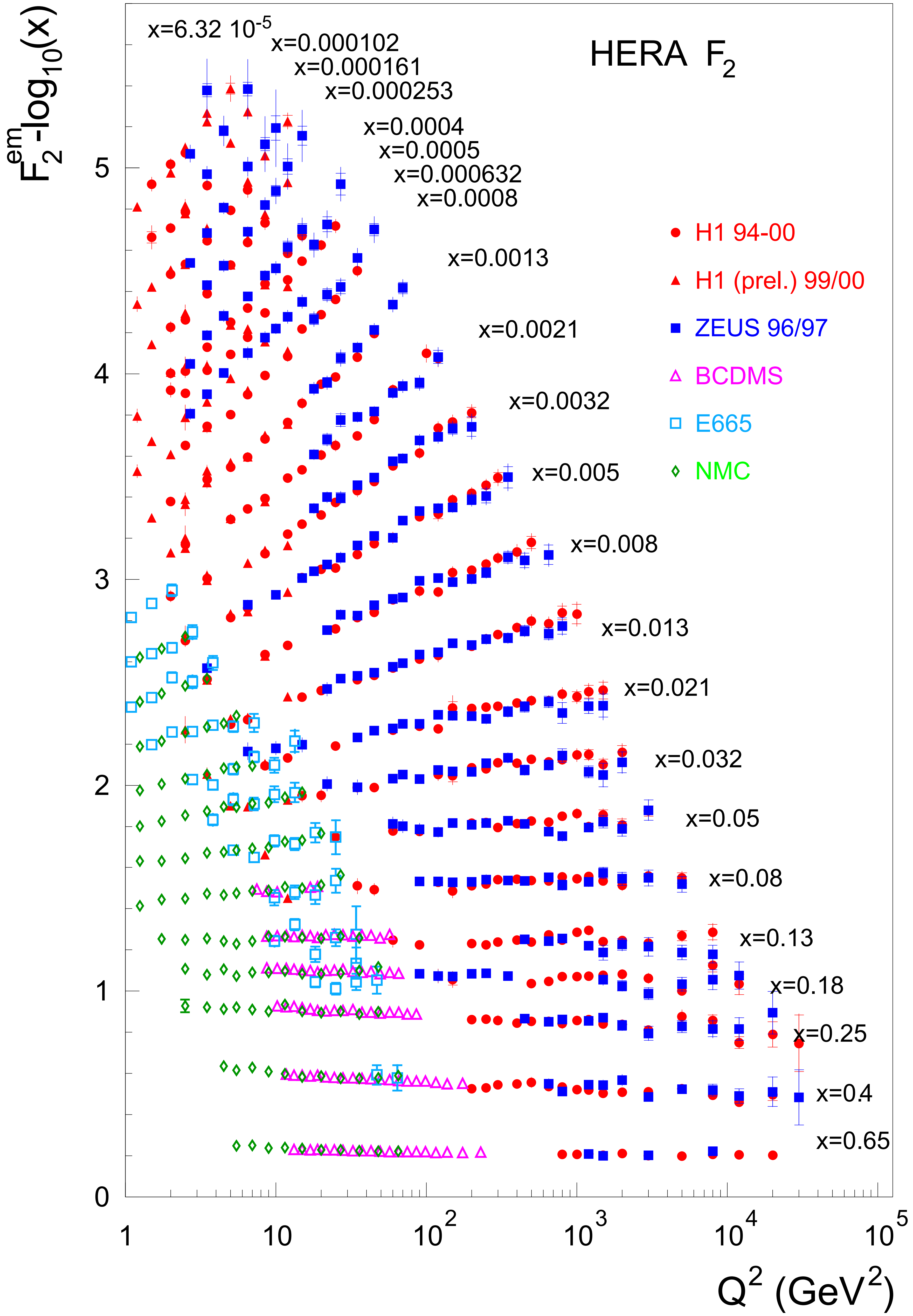

Bjorken Scaling: $F_2(x, Q^2) \neq F_2(x)$

Broken - Big Time

It's the **Glue !!!**

Quark and Gluon Distributions

Structure functions allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions.

In LO: Probability to find parton with x, Q^2 in proton

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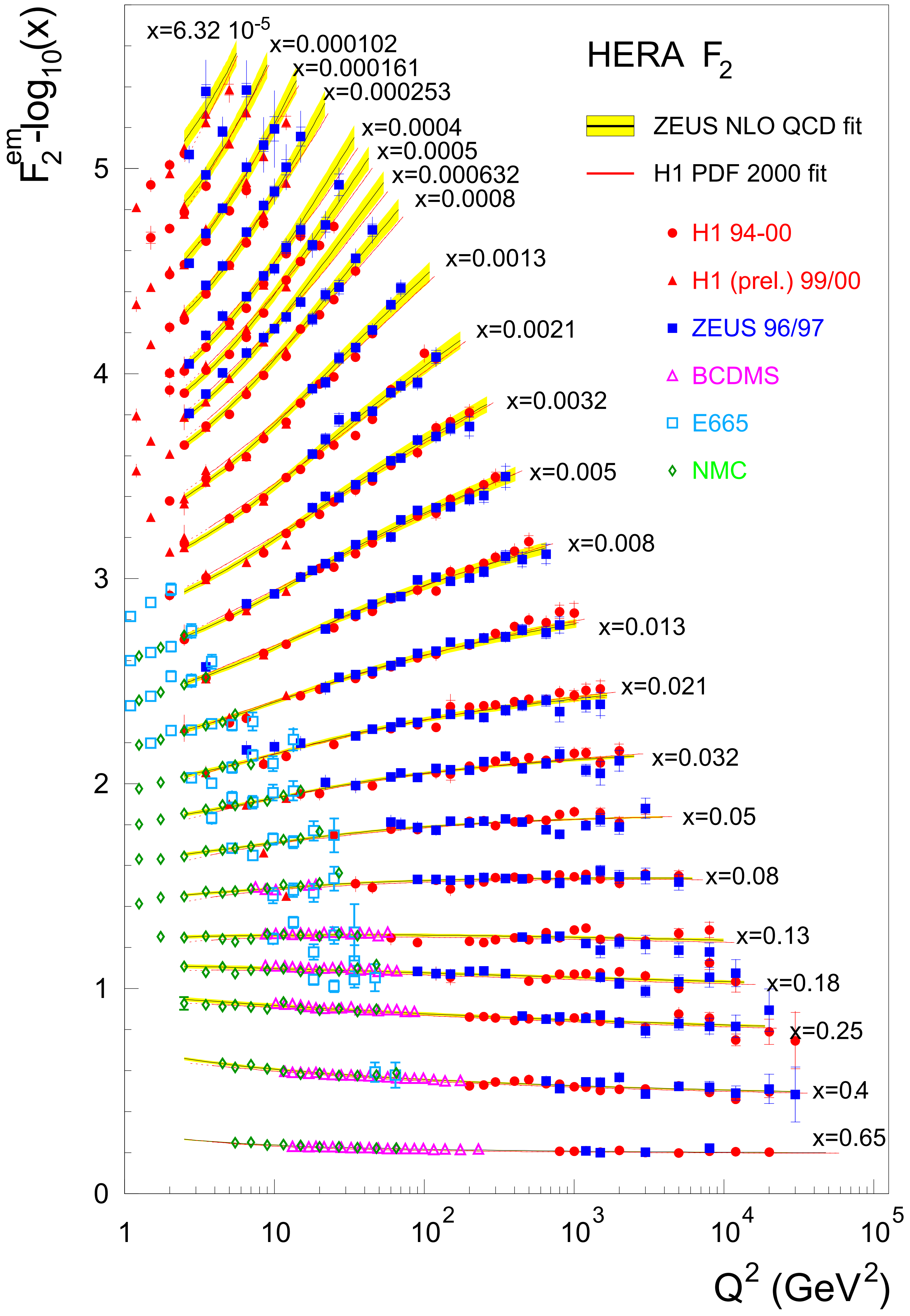

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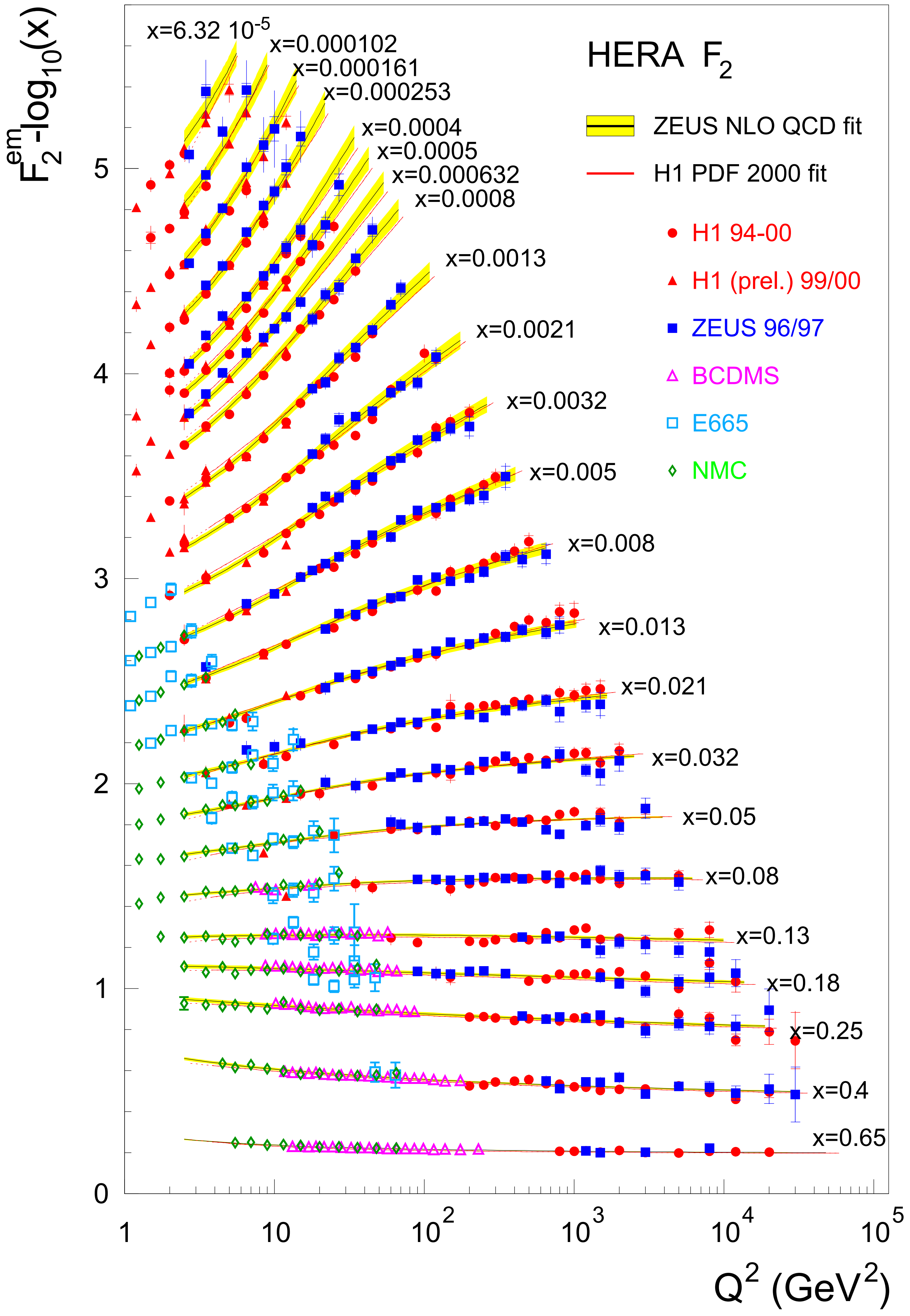

$\Longrightarrow$

- F_2
- $dF_2/dlnQ^2$

\+ pQCD+ DGLAP Evolution

$$f(x,Q_1^2) \rightarrow f(x,Q_2^2)$$

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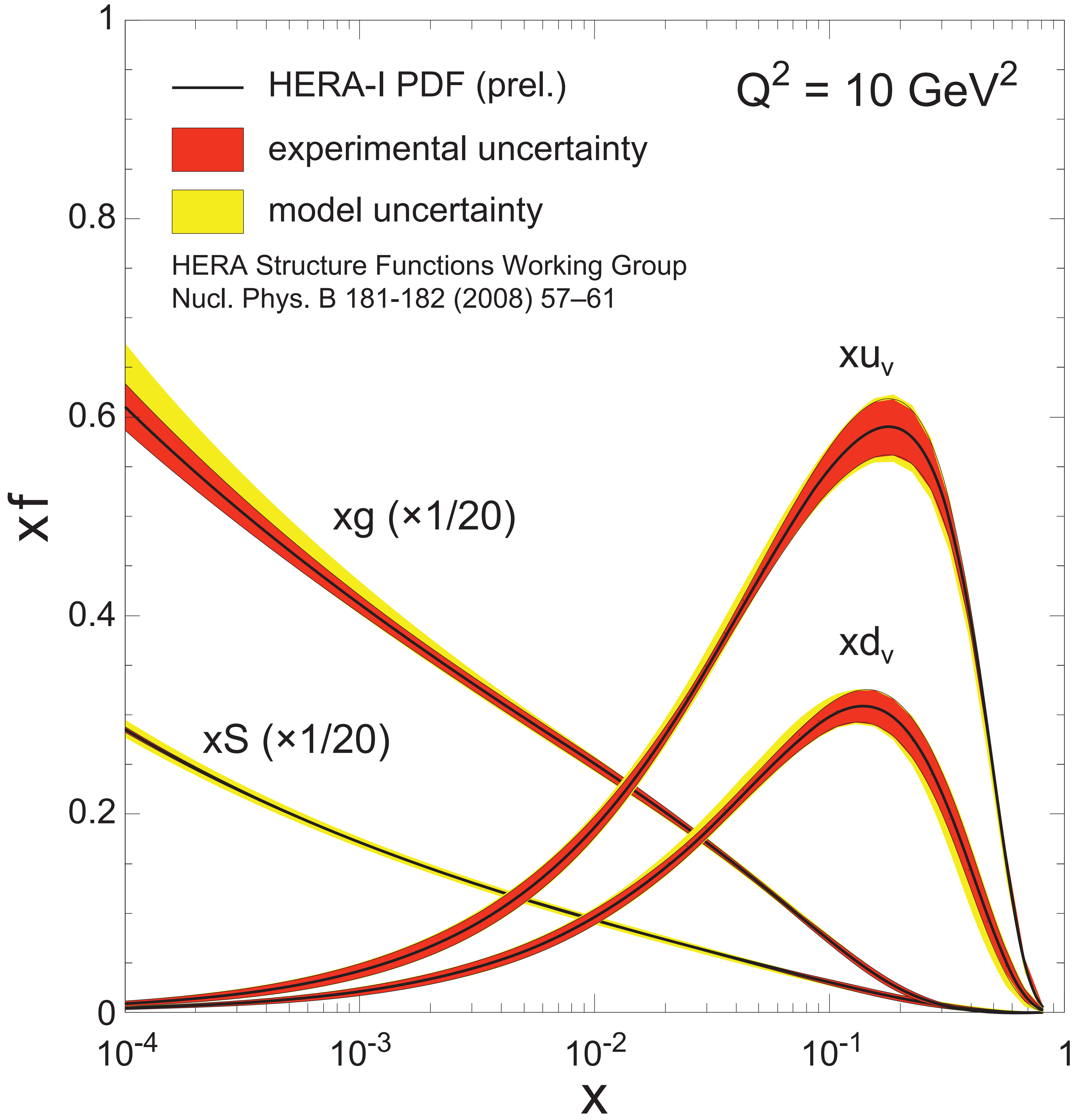

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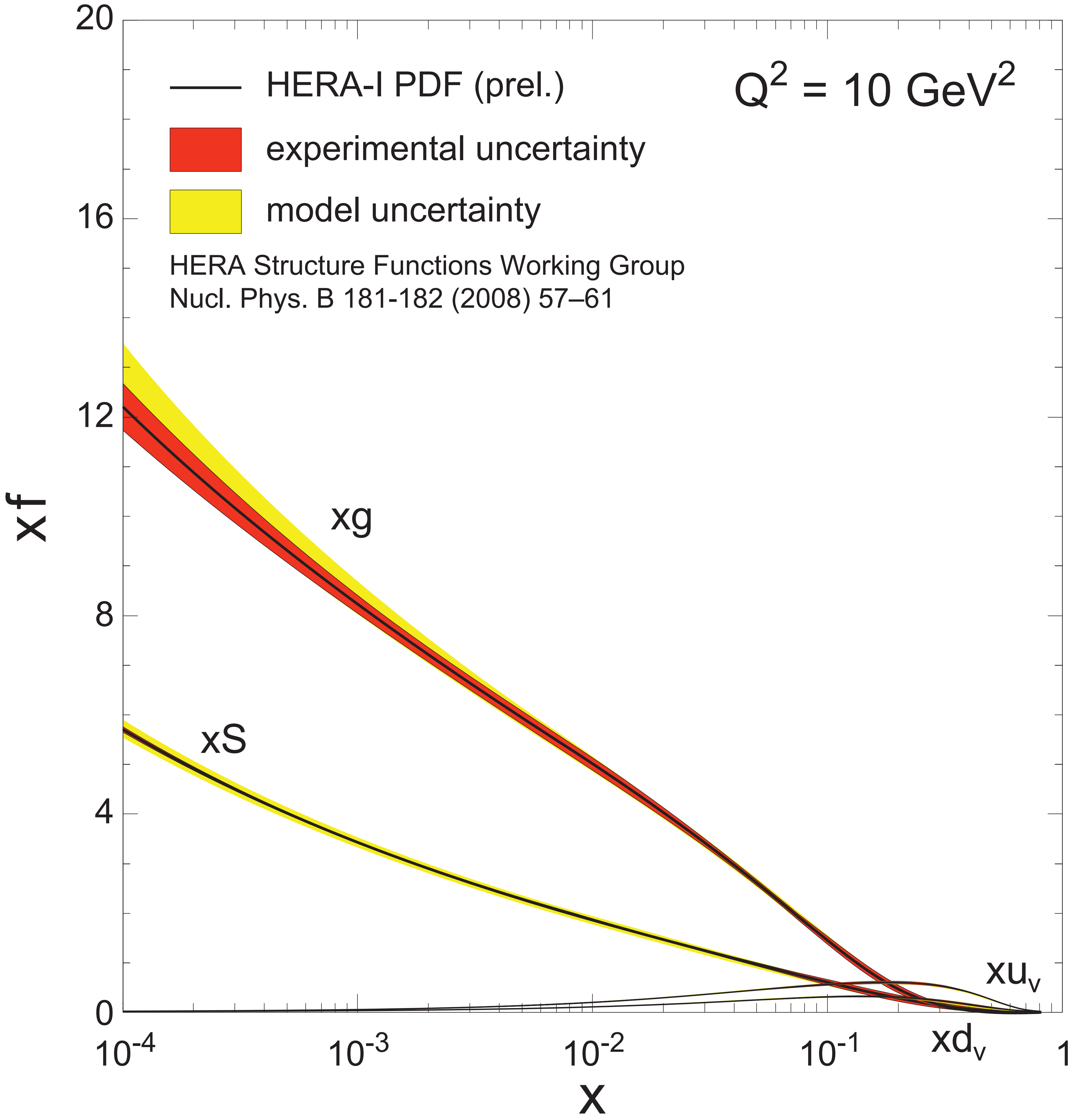
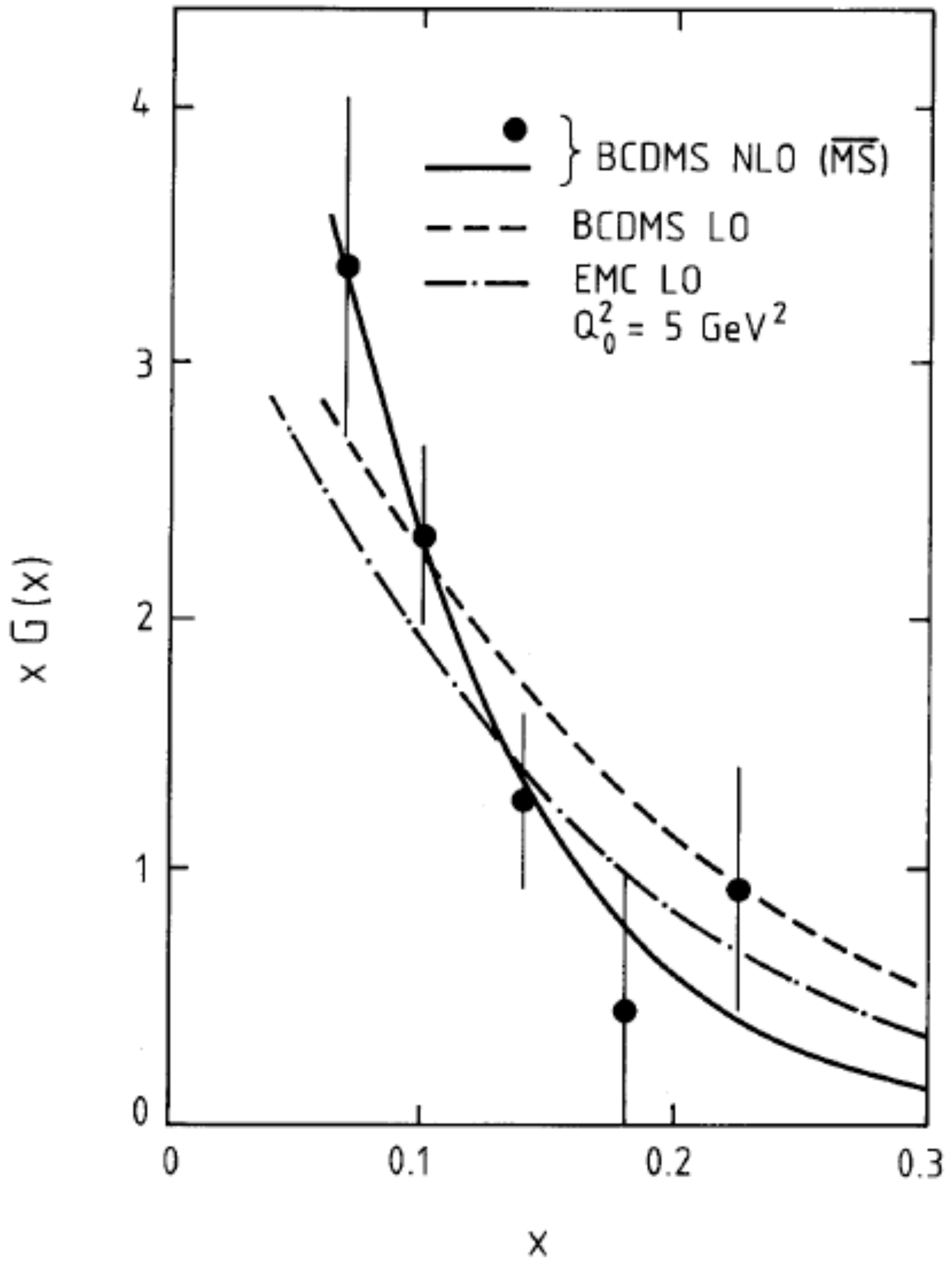


Proton is almost entirely glue by x<0.1 (for Q^2 = 10 GeV^2)

Hera's Impact

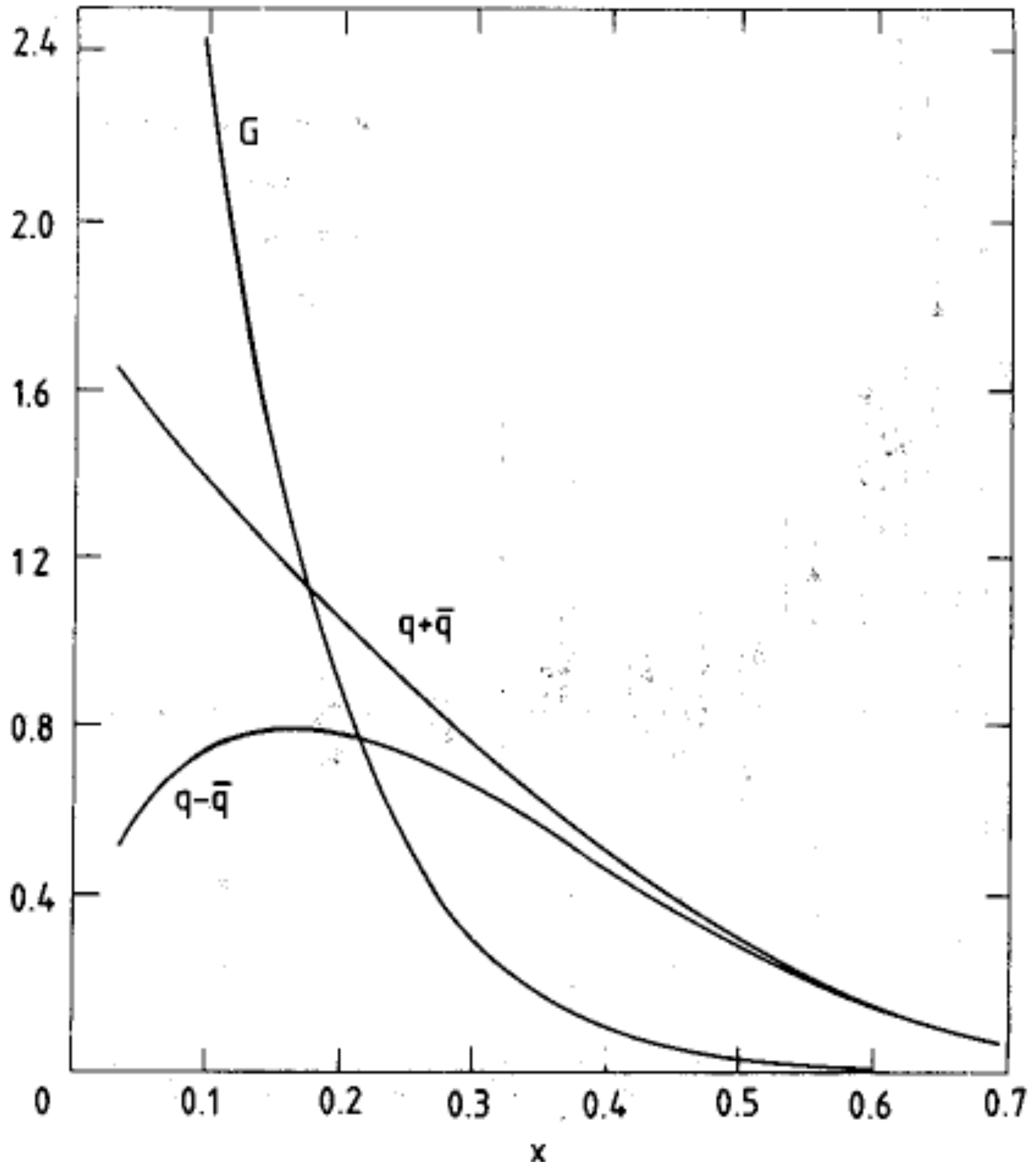
PDFs before HERA - Gluon - $xg(x,Q^2)$

BCDMS



CERN-EP/89-07
January 17th, 1989

CDHS

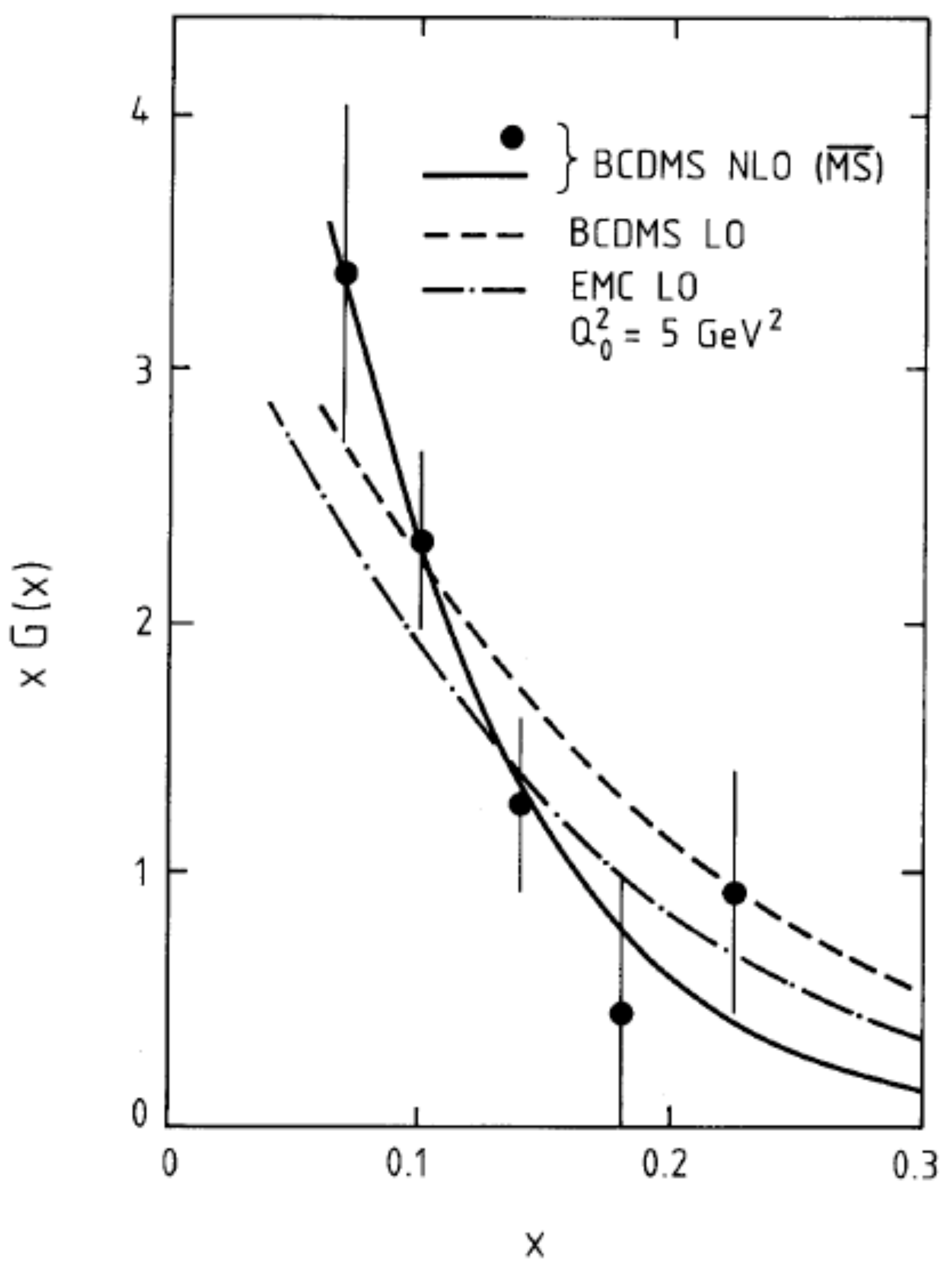


CERN-EP/89-103
15 August 1989

Hera's Impact

PDFs before HERA - Gluon - $xg(x,Q^2)$

BCDMS



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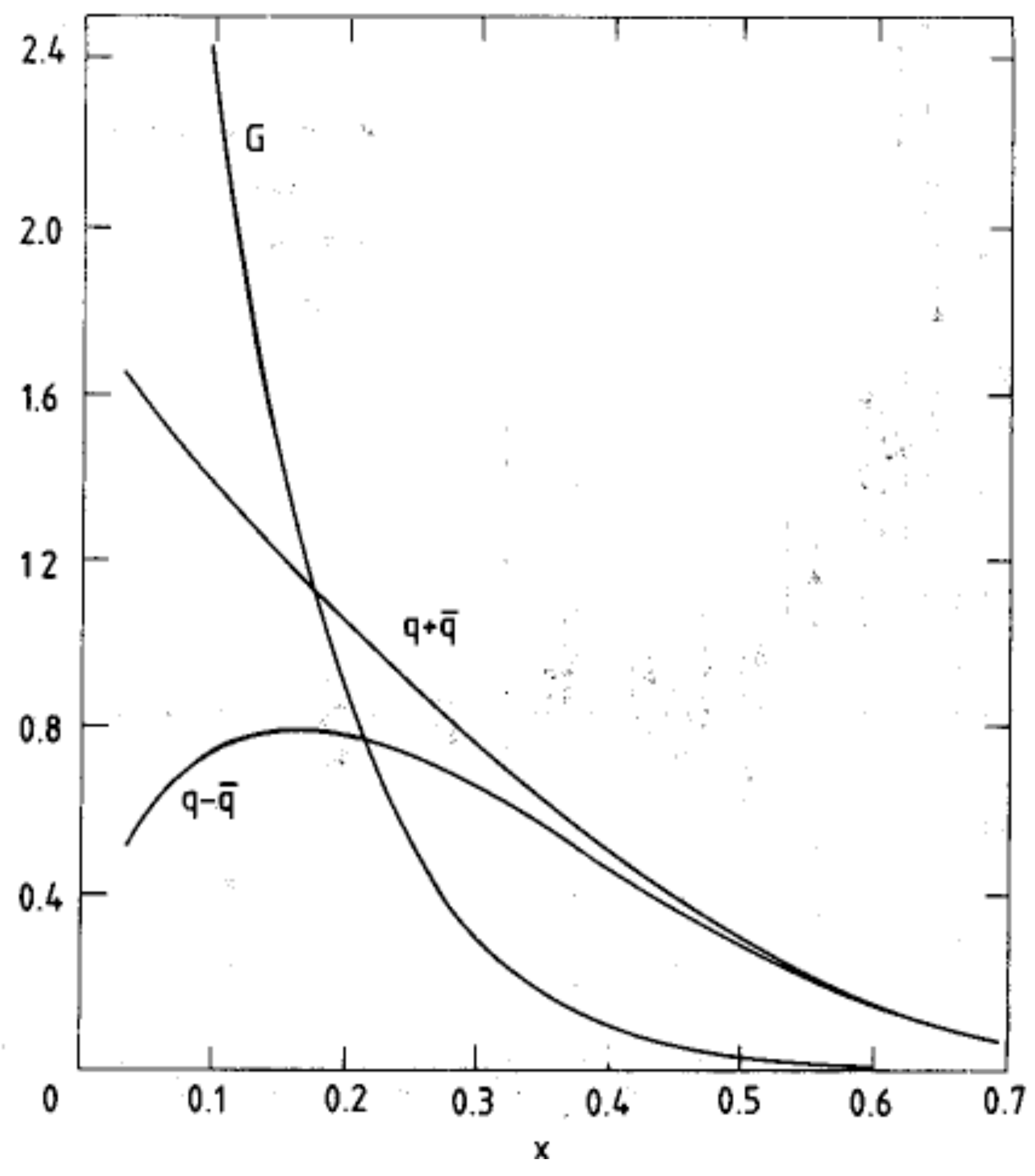

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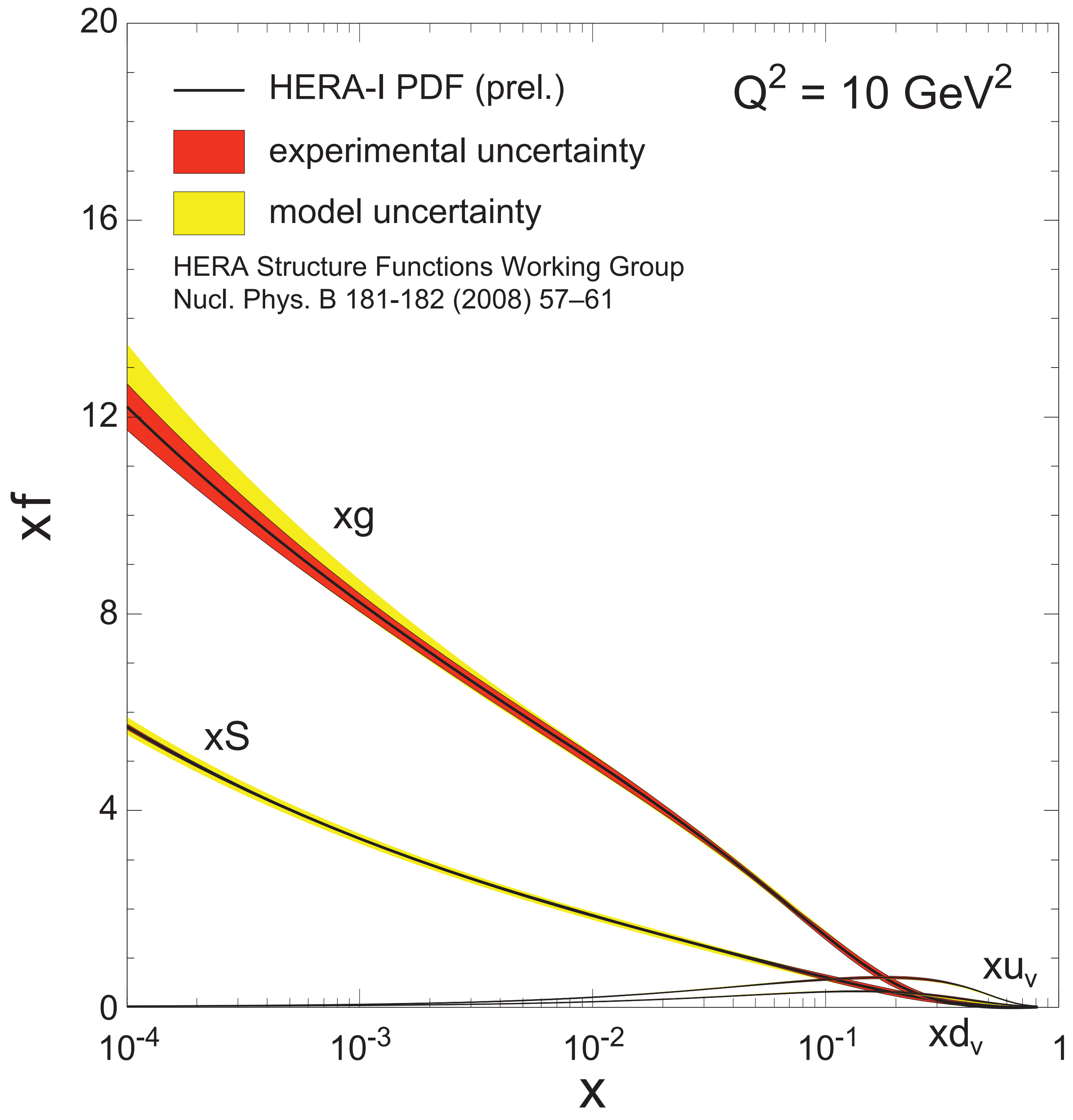
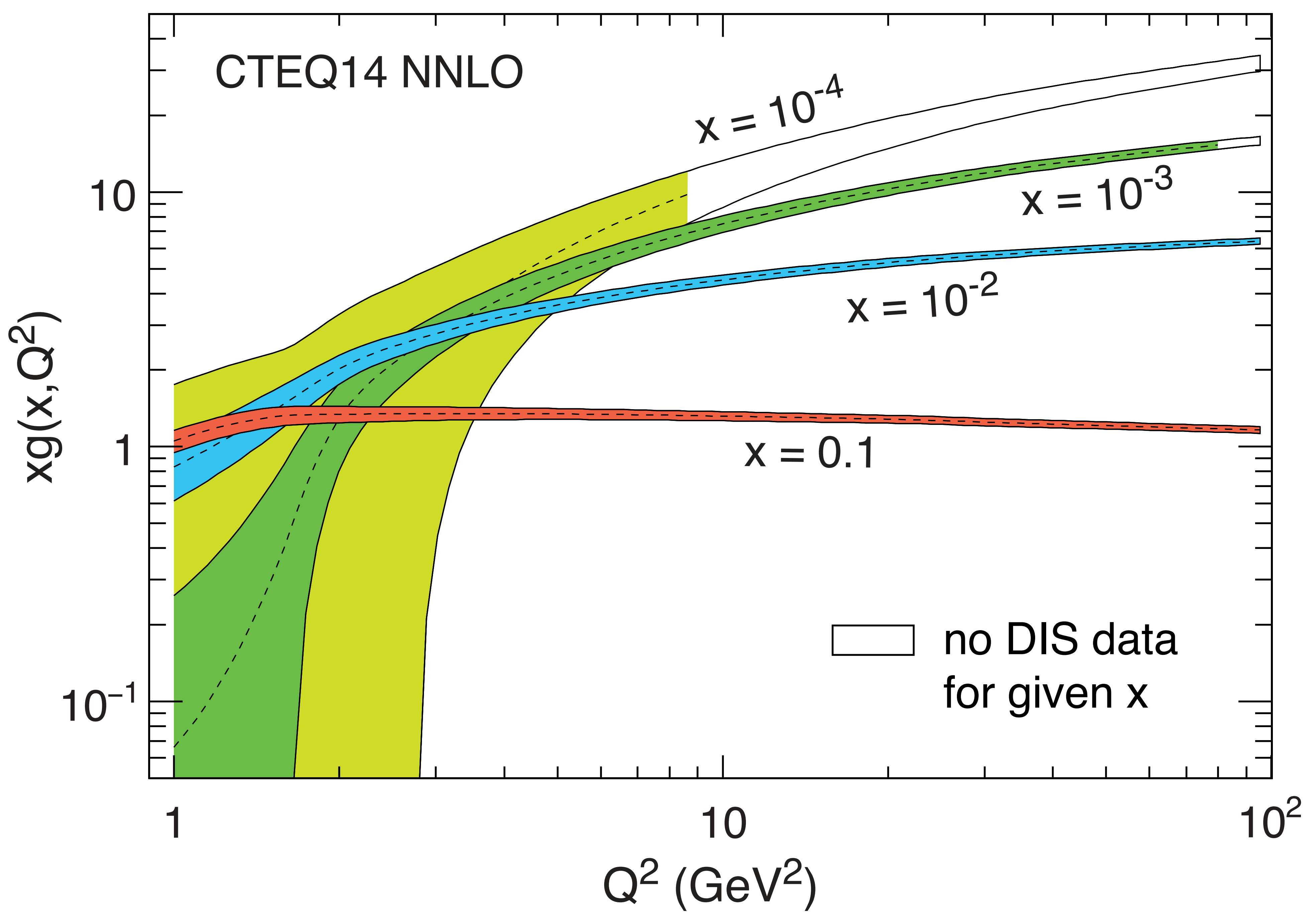


PDFs: Much Progress, Still Shortcomings

- Quarks: $q_i(x,Q^2)$ from F_2 (or reduced cross-section)
- Gluons: $g(x,Q^2)$ through scaling violation: $dF^2/d\ln Q^2$

e.g. CTEQ14: a modern proton PDF

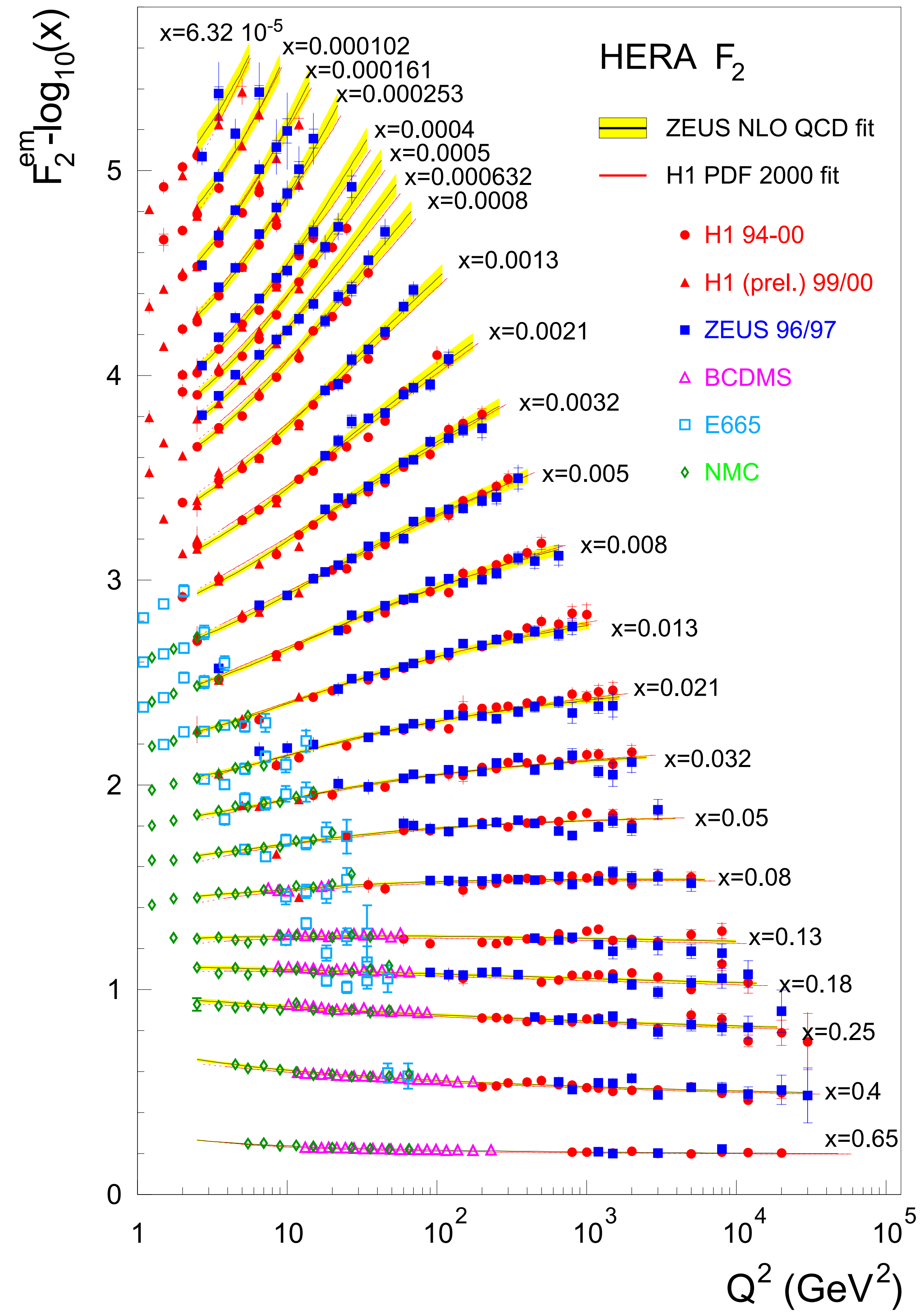


- Large uncertainties at $x=10^{-3}$ and 10^{-4} at the small Q^2 although high quality data exist.
- The precision of low Q^2 data is ineffectual due to the lack of data at the larger Q^2 (Evolution from low to high Q^2)

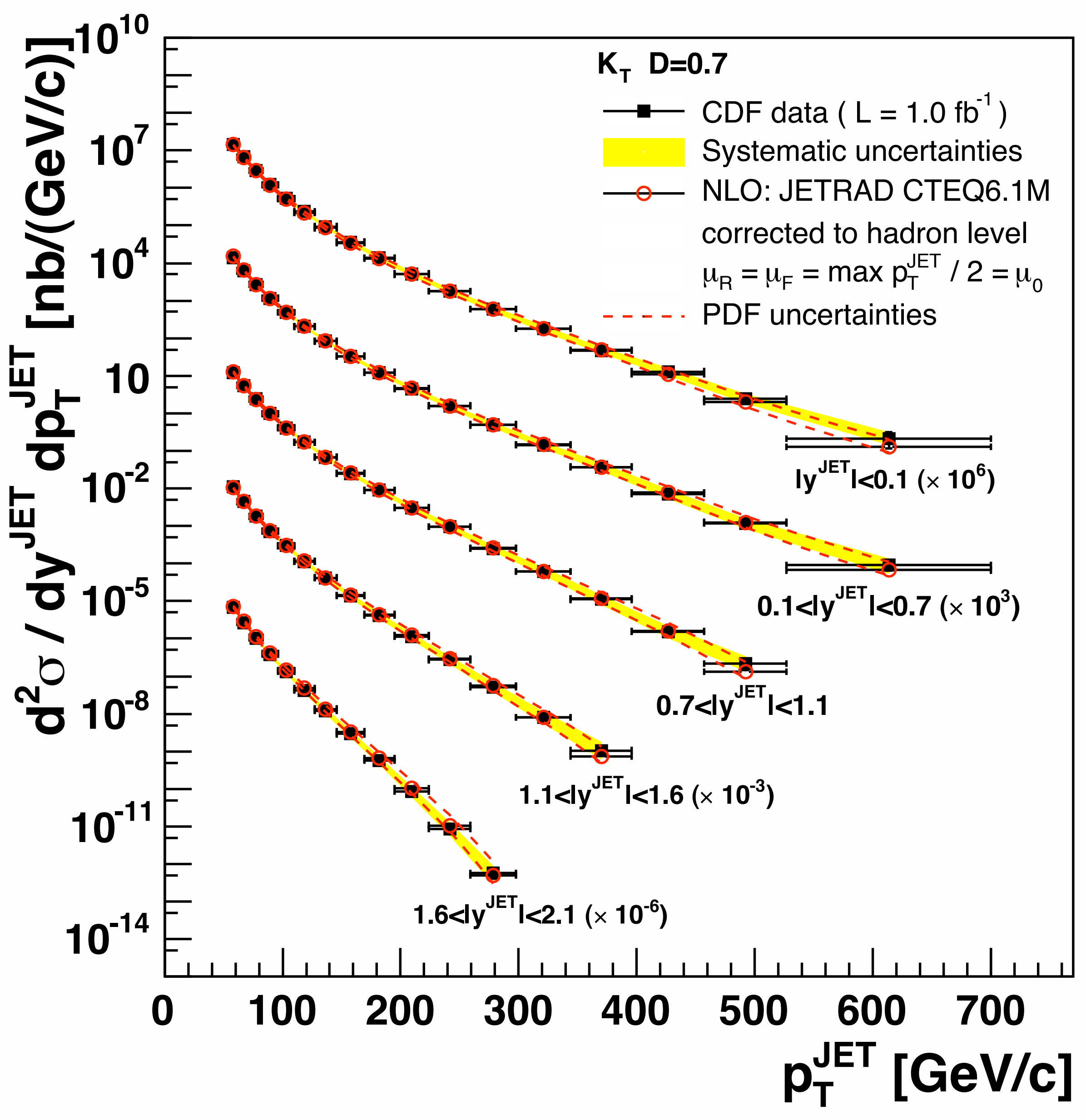
Uncertainties from PDF dominate many “BSM” searches

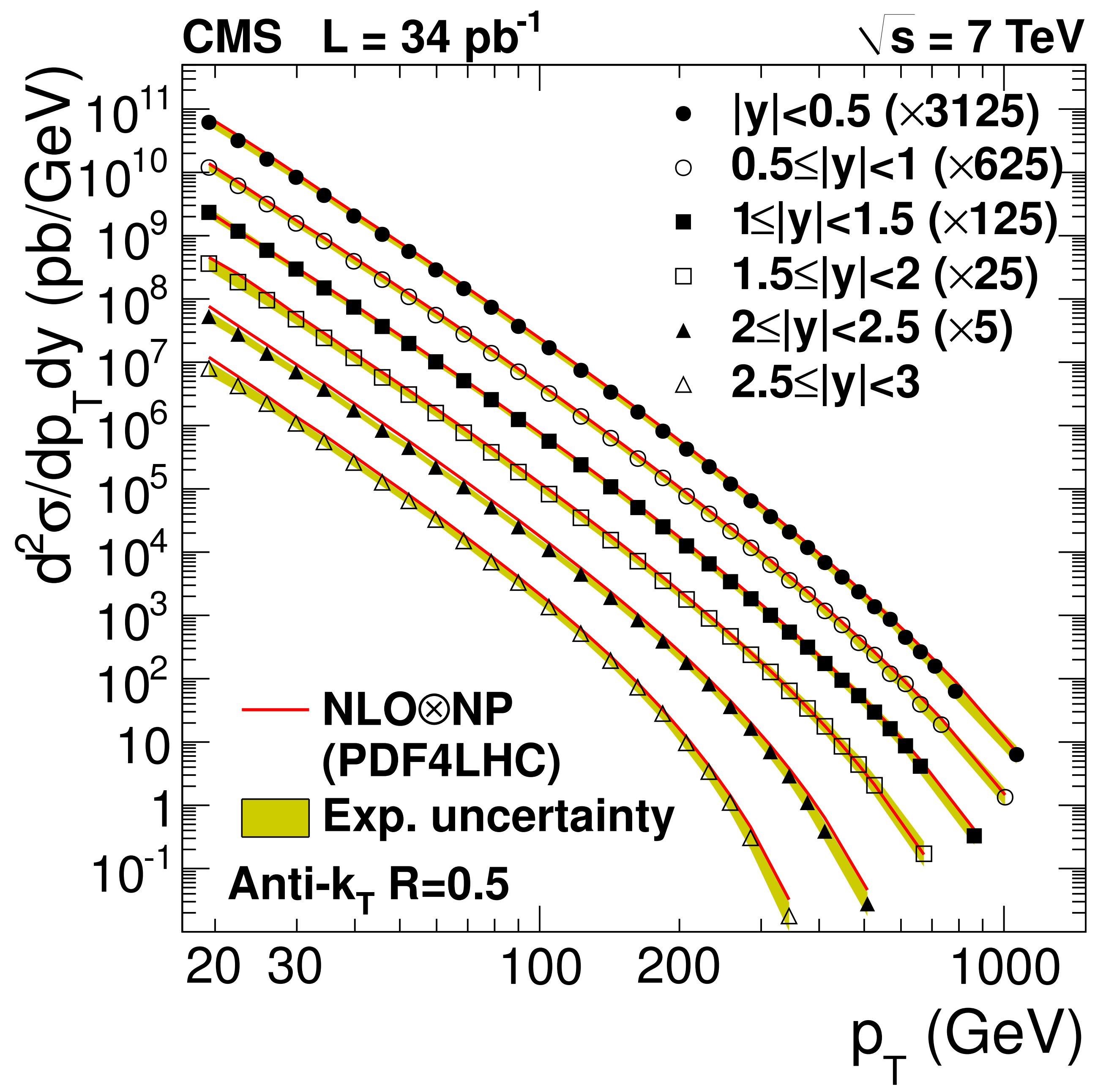
Strong Evidence that QCD is the Correct Theory

Structure functions measured at HERA ep collider

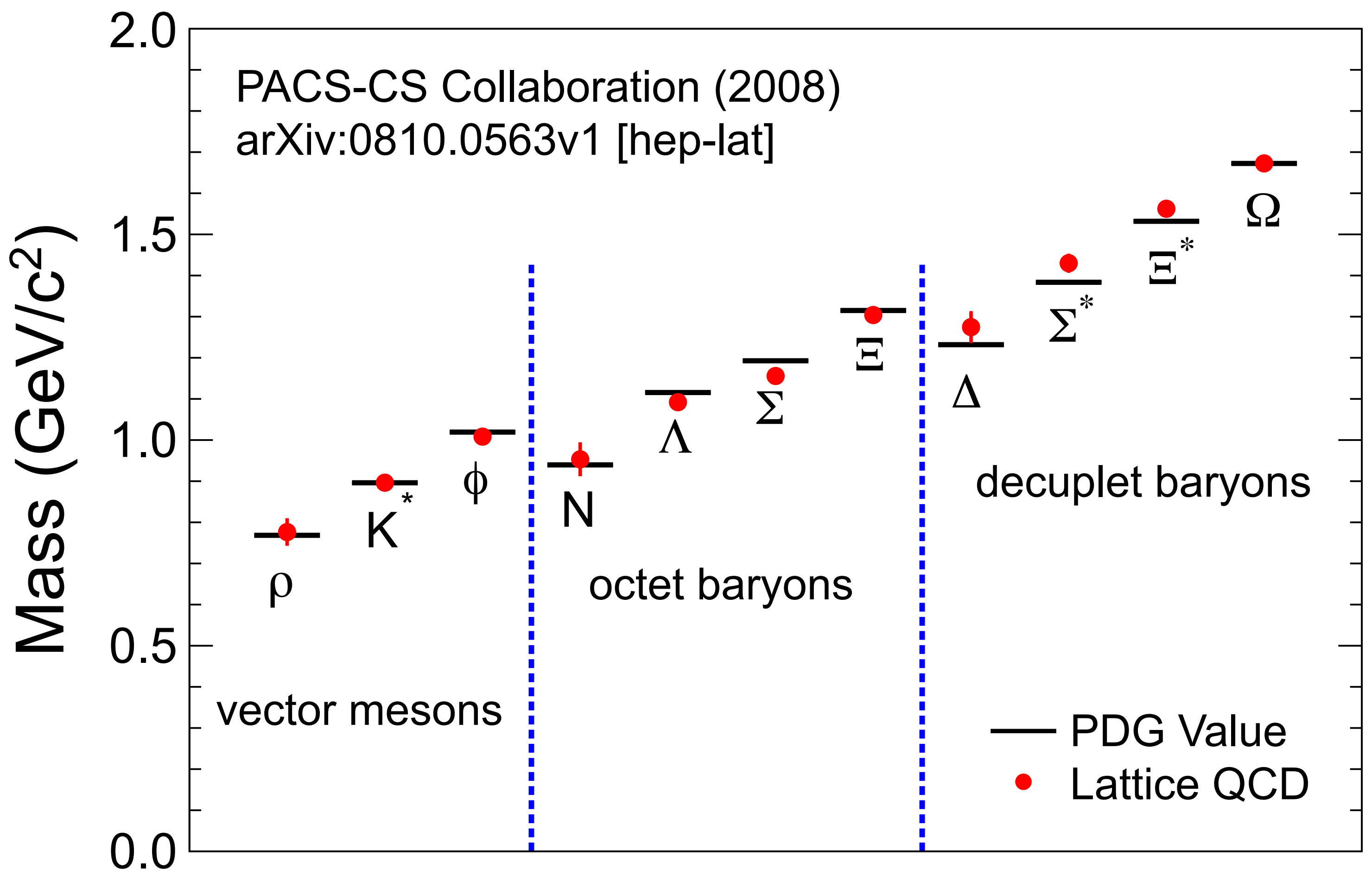


Jet cross-sections: pp collisions at LHC and $\bar{p}p$ collisions at Fermilab





Lattice QCD



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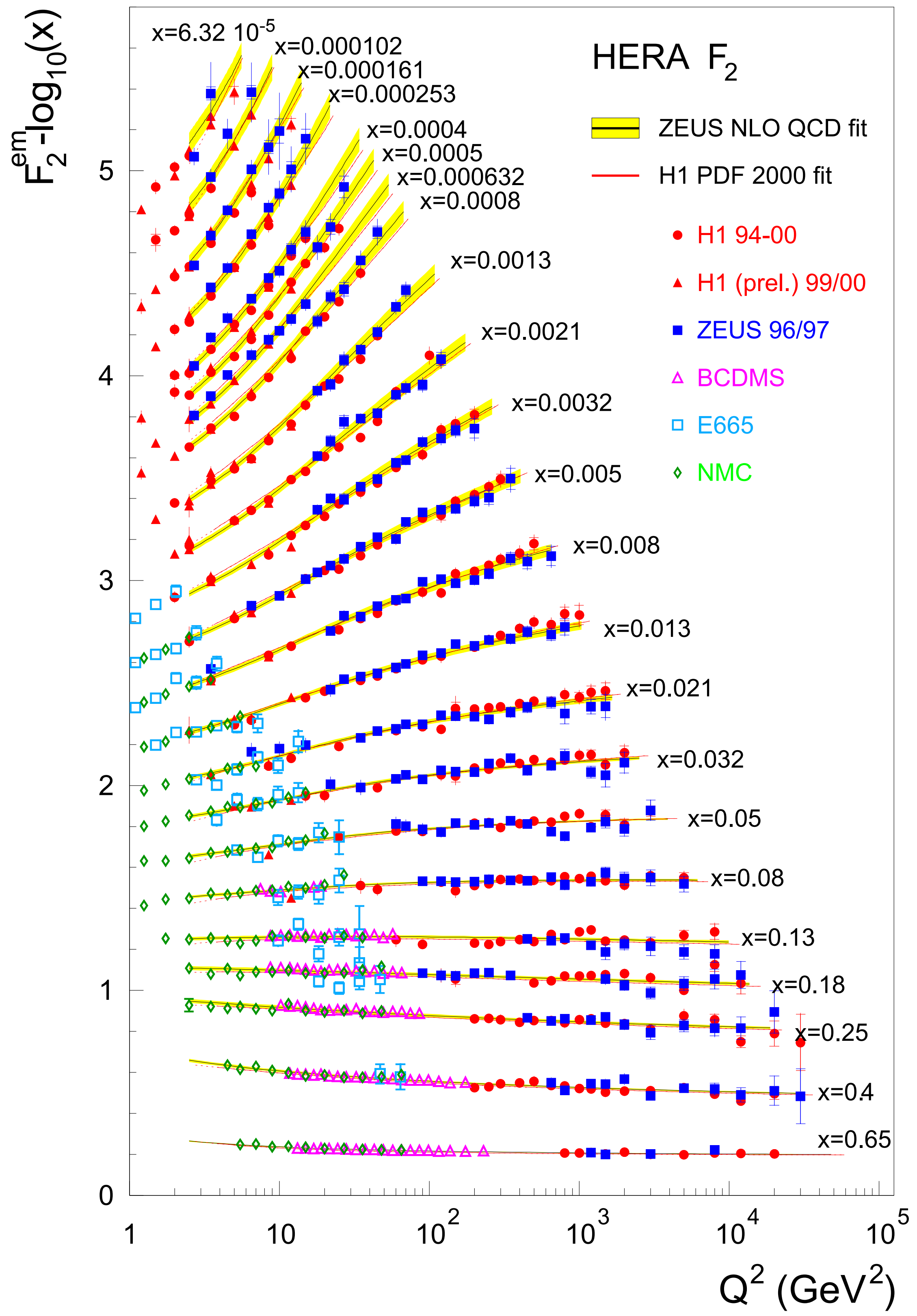

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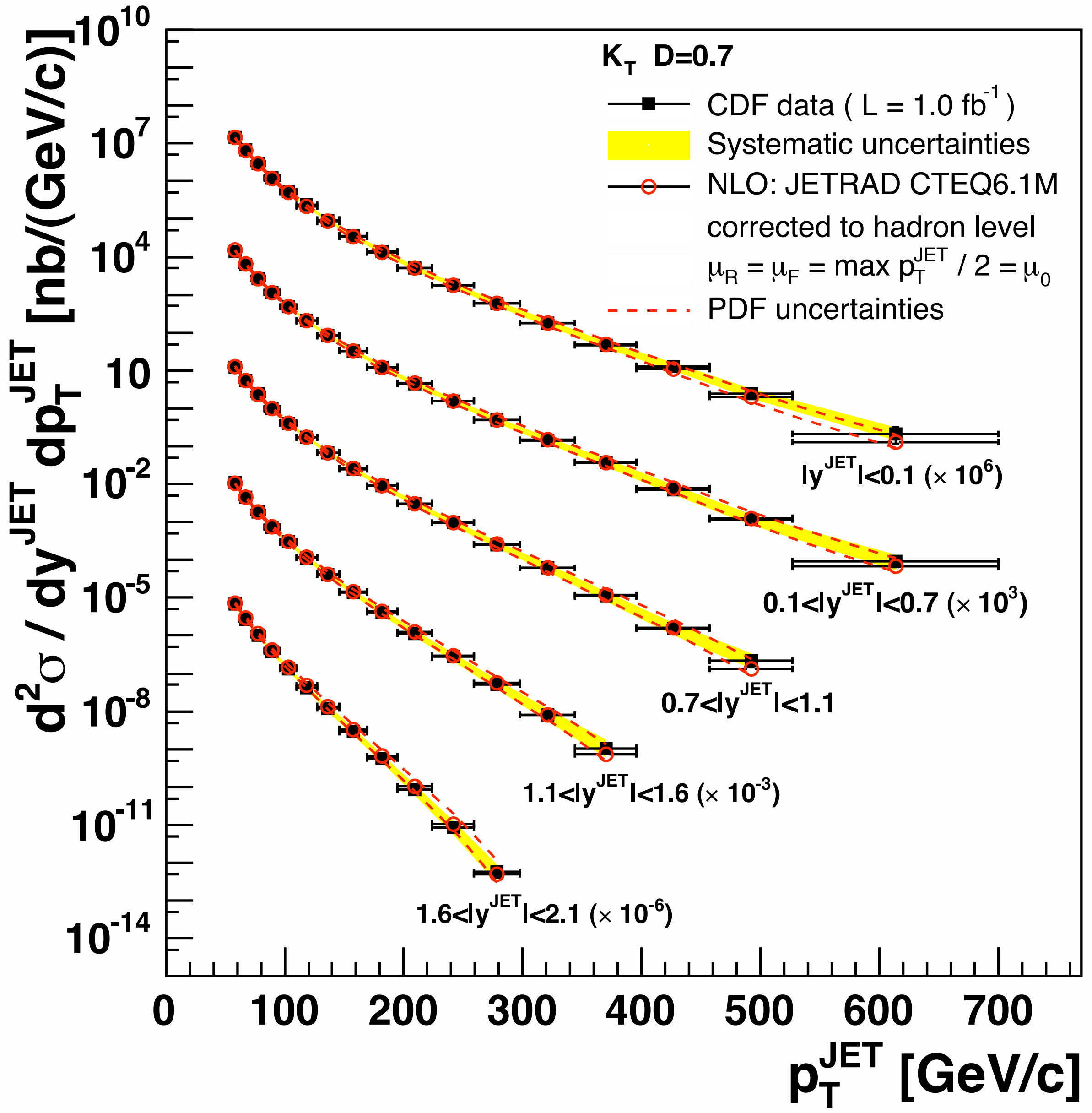

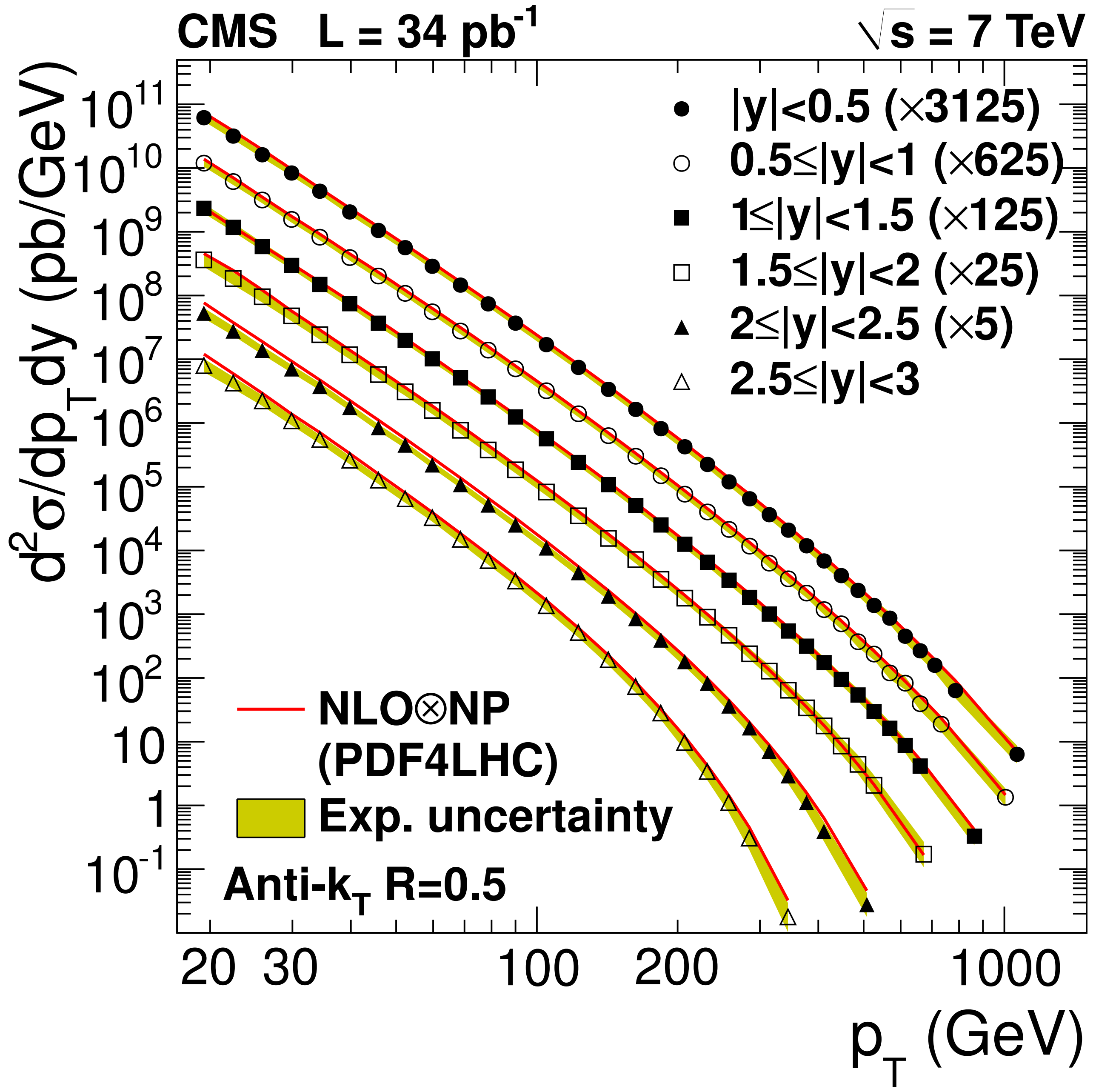

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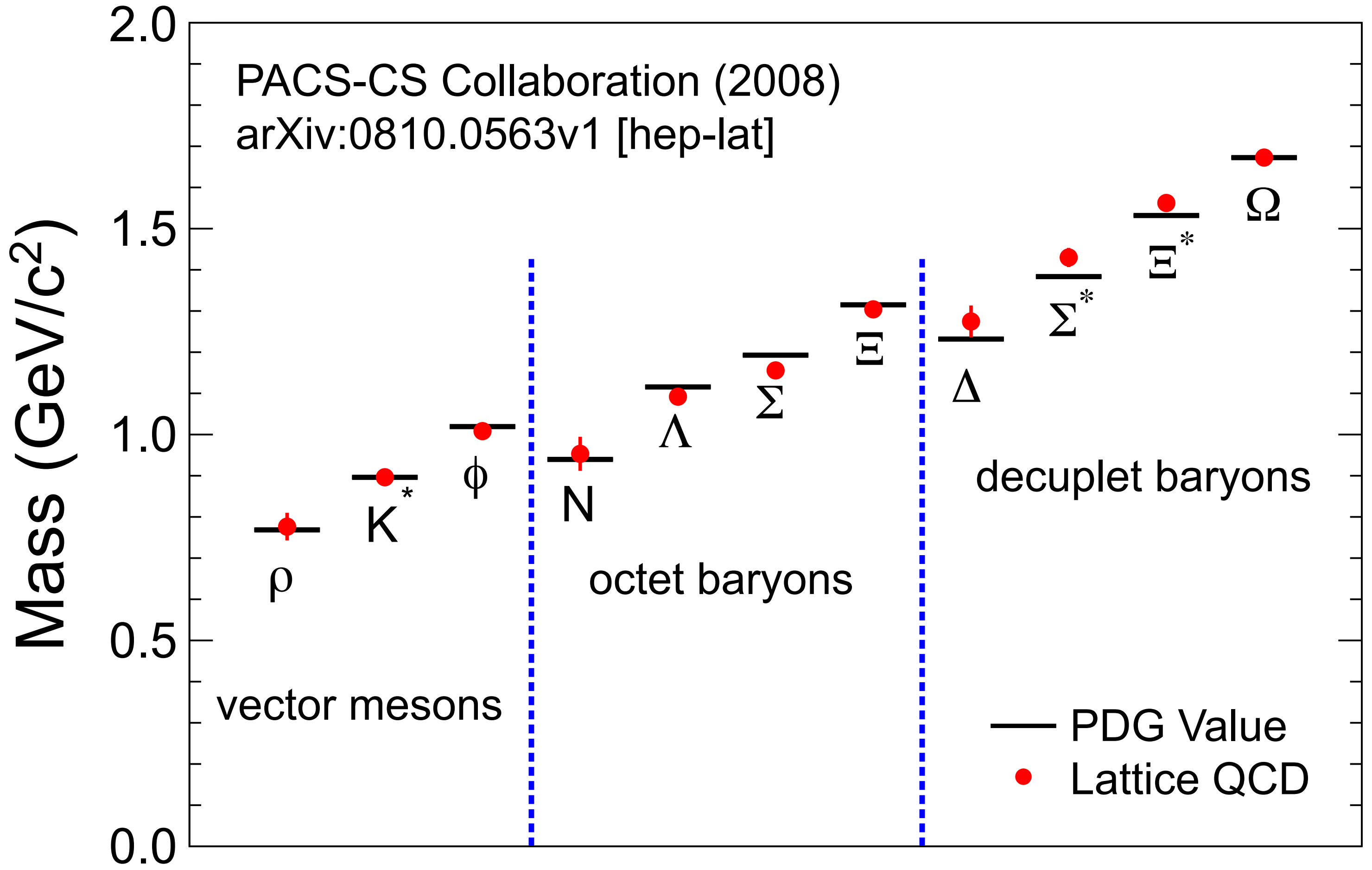
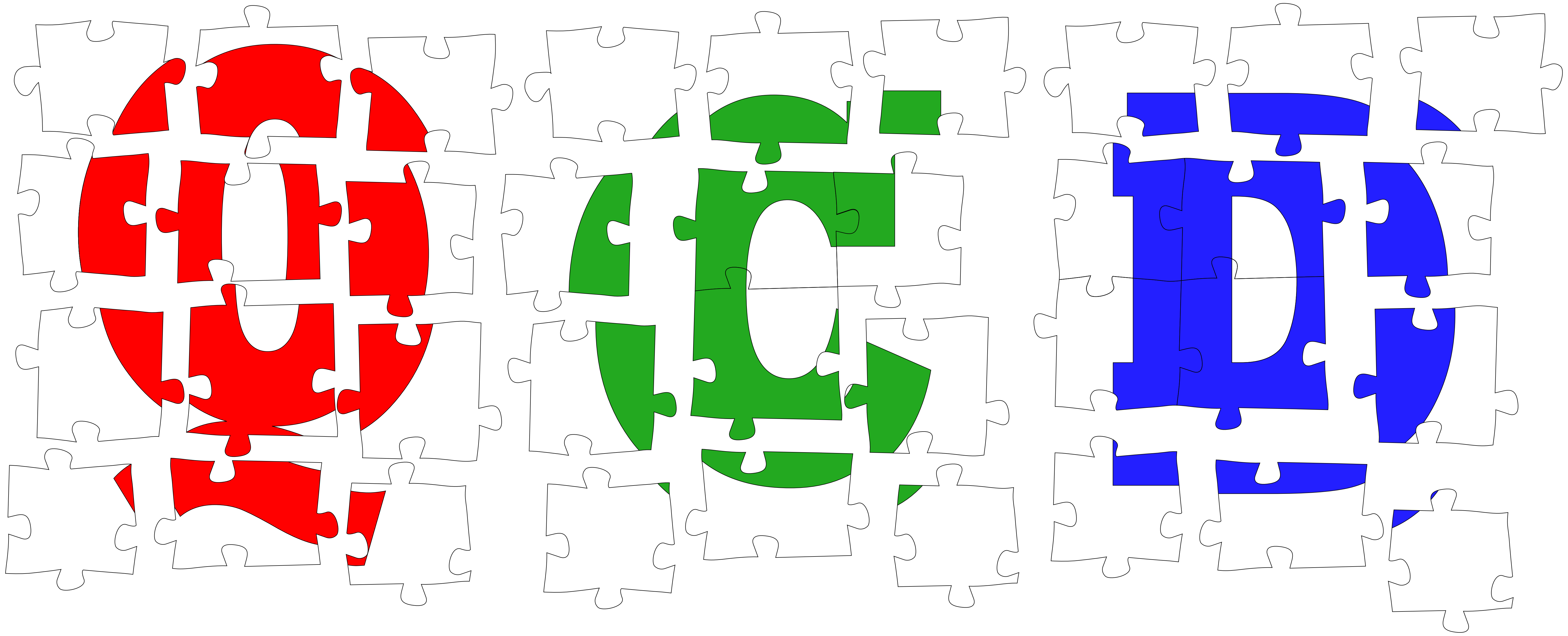


Are we done?

3. The Frontiers of Our Ignorance



... that motivate an Electron-Ion Collider

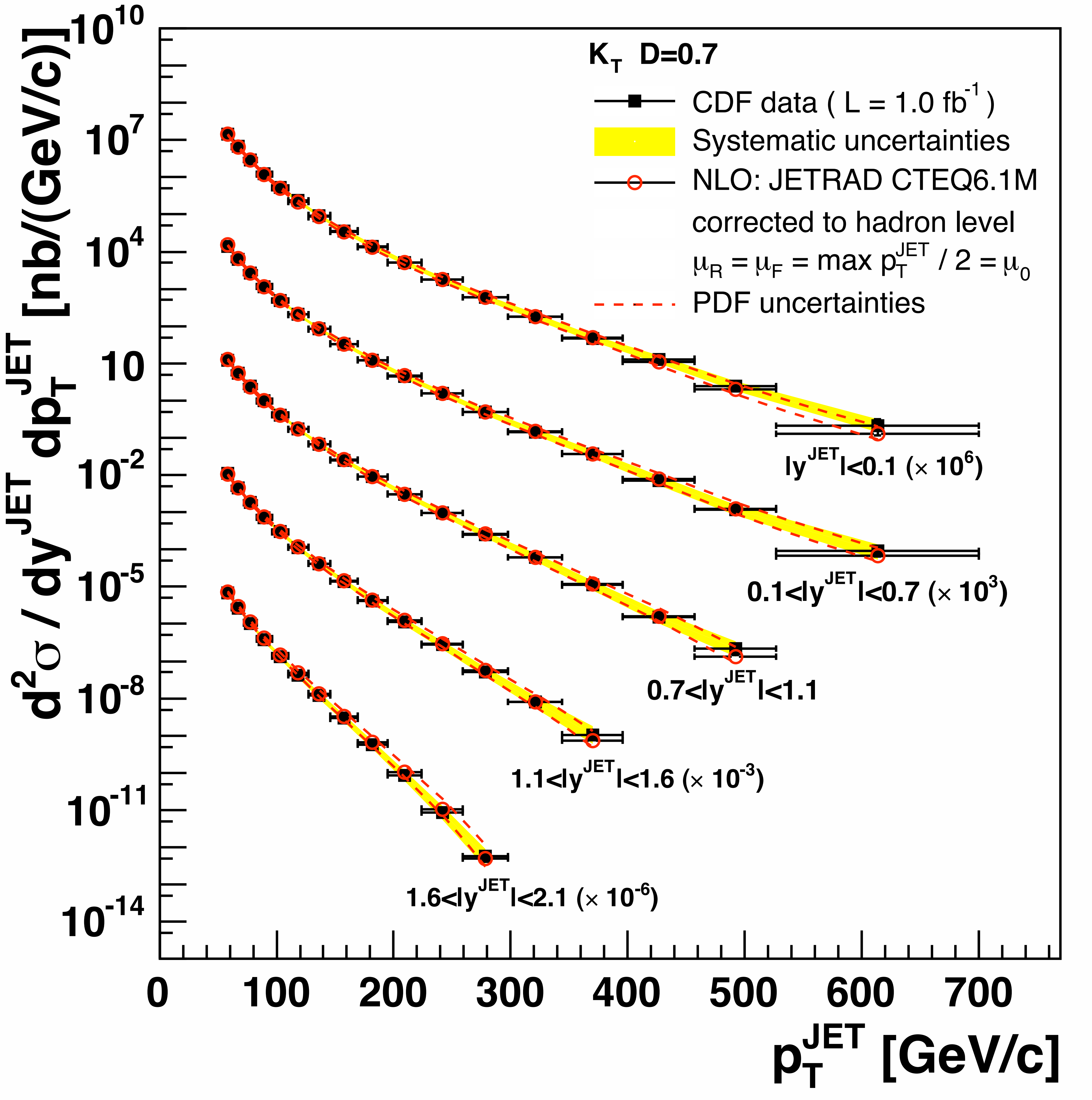
Scattering in the Strong Interactions

Perturbative QCD:

- Describes only a small part of the total cross-section

Lattice QCD:

- First principles treatment of static properties of QCD: masses, moments, thermodynamics
- Very challenging for dynamical processes and very limited utility in describing scattering



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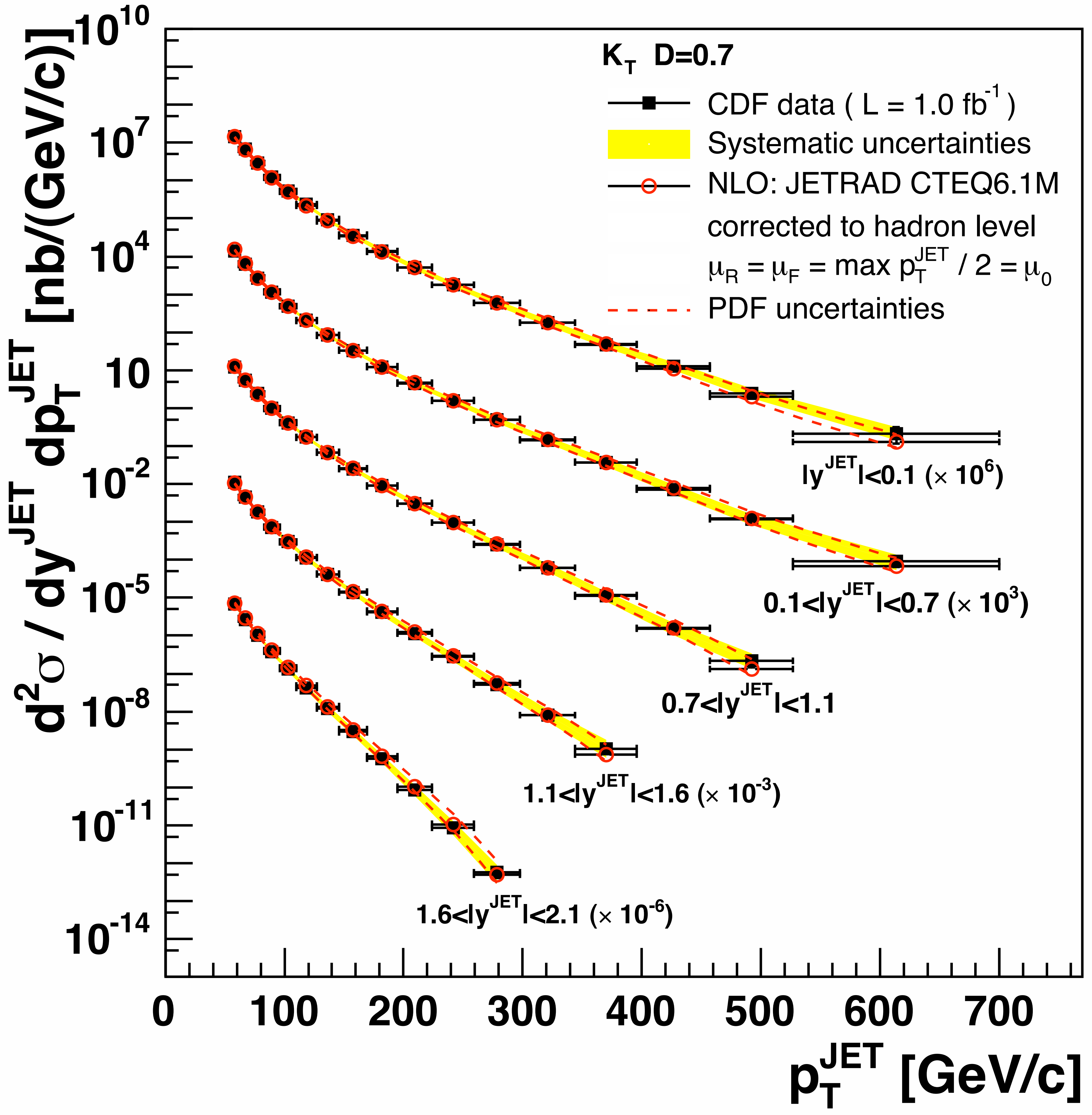
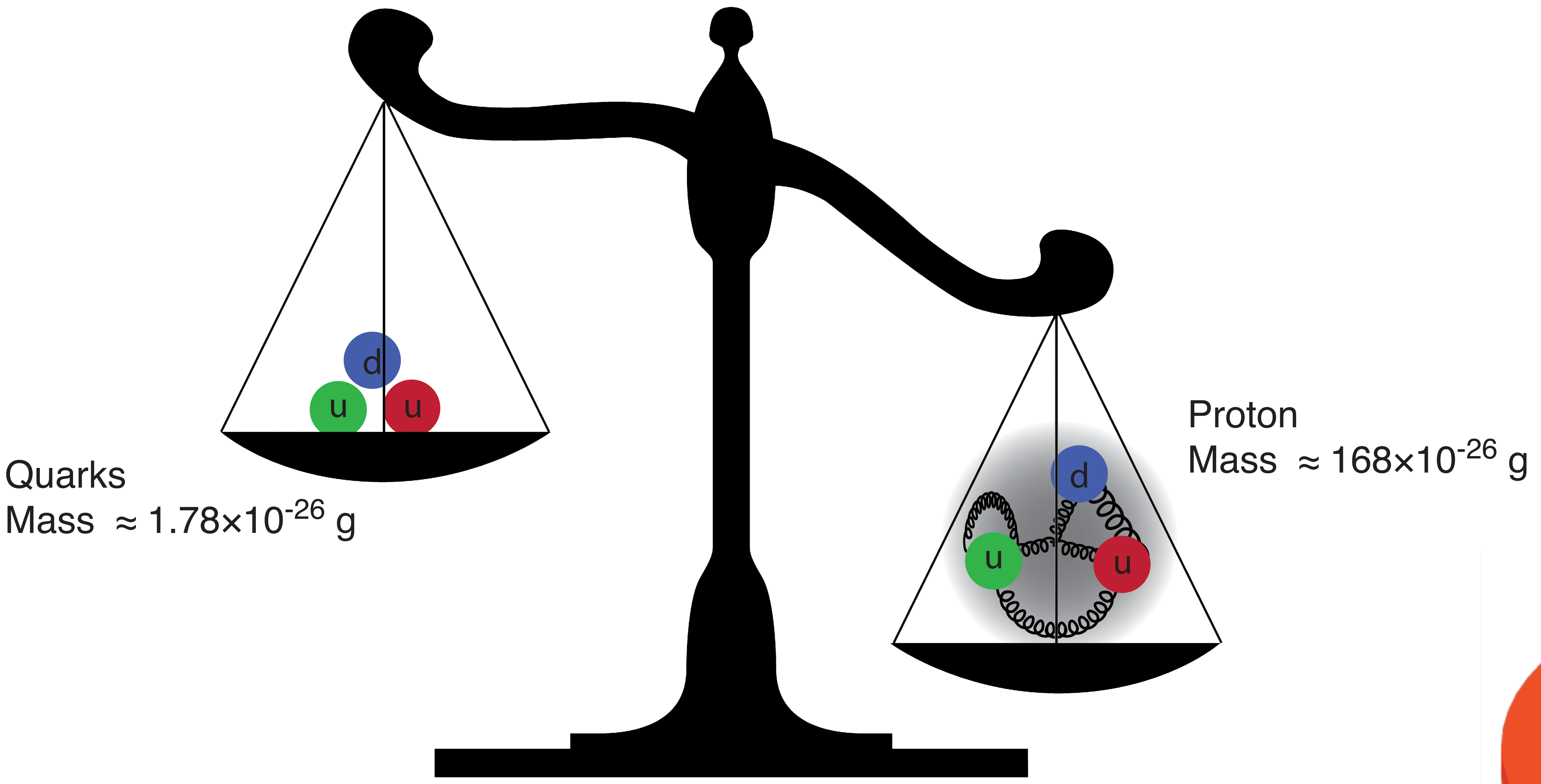
Instead ⇒ Effective theories:

- How do quark and gluon degrees organize themselves to describe the bulk of the cross-section?

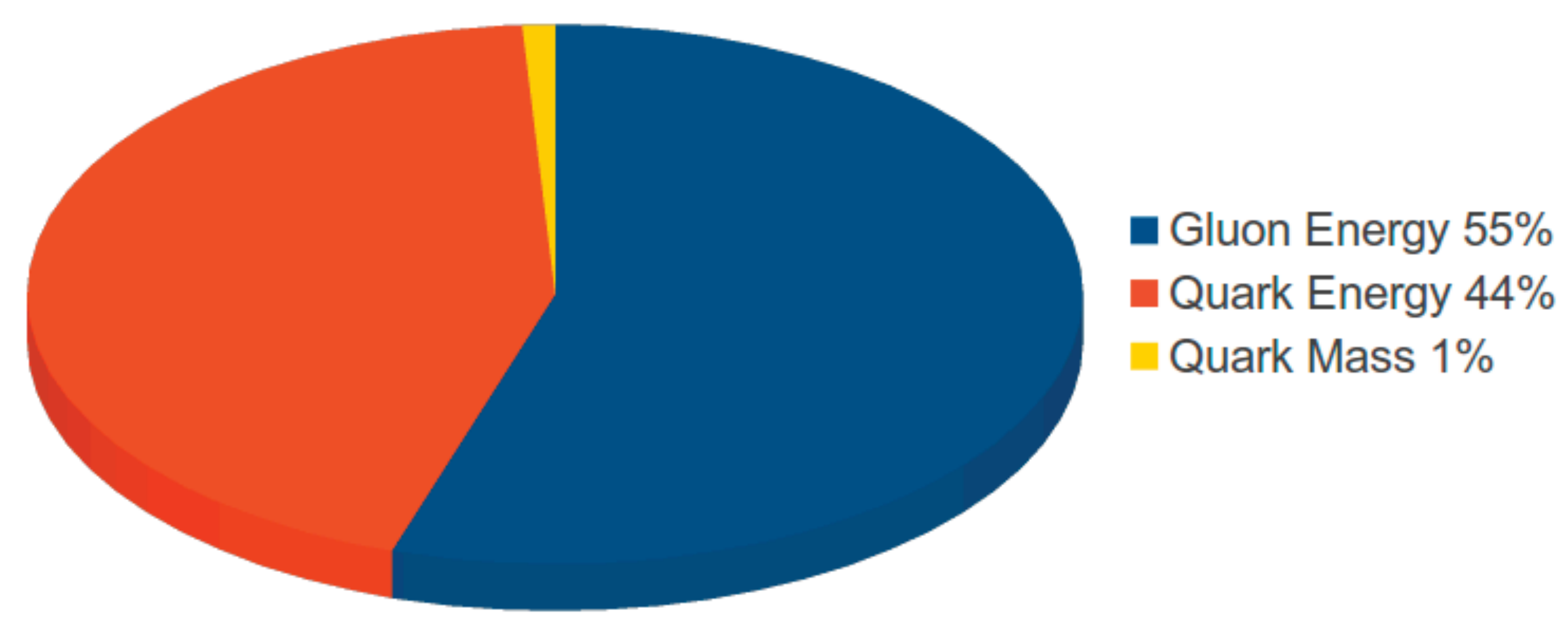


The Mass Puzzle

Gluons are massless…yet their dynamics are responsible for (nearly all) the mass of visible matter. We do not know how?



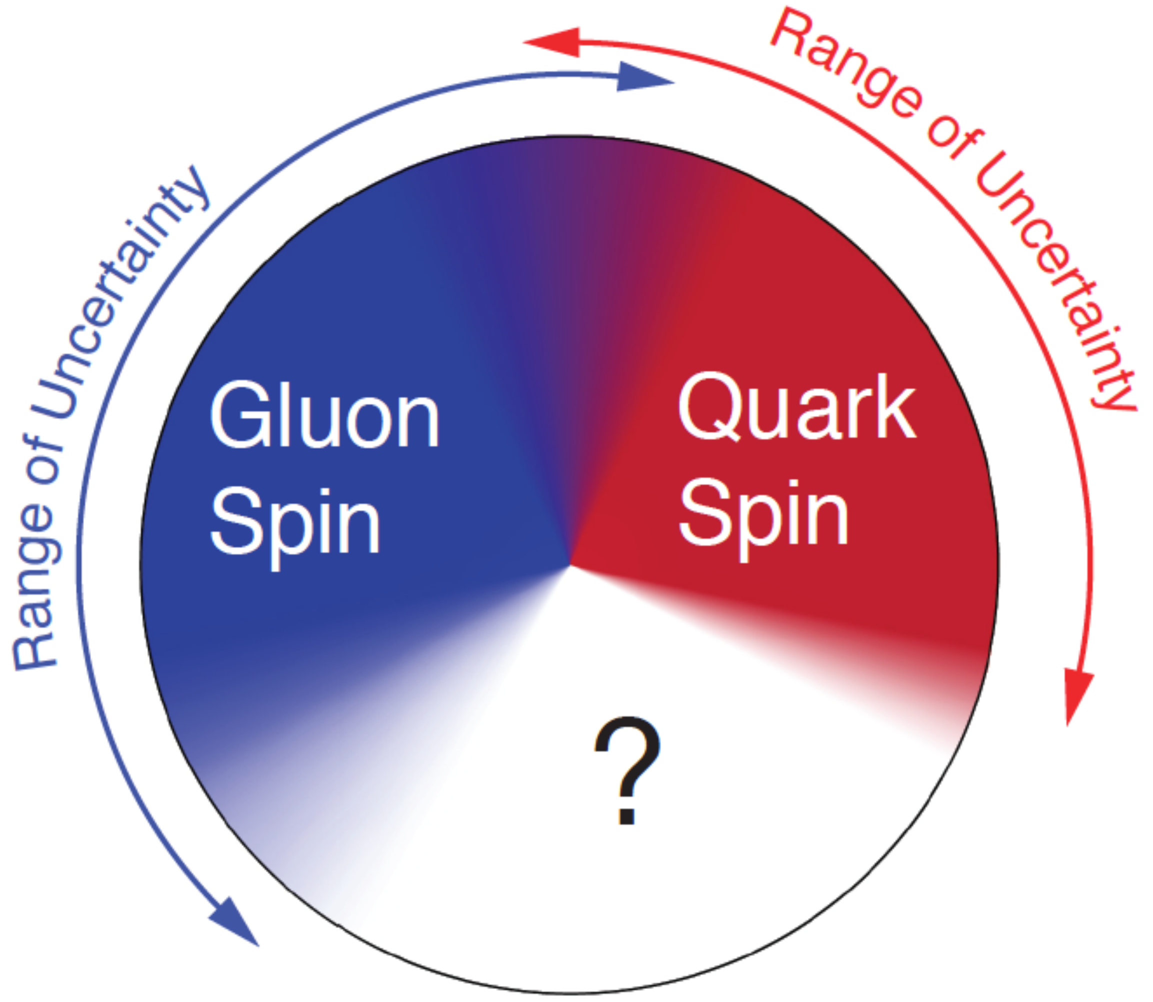
The Higgs field is responsible for quark masses that make ~ 1% of the proton mass



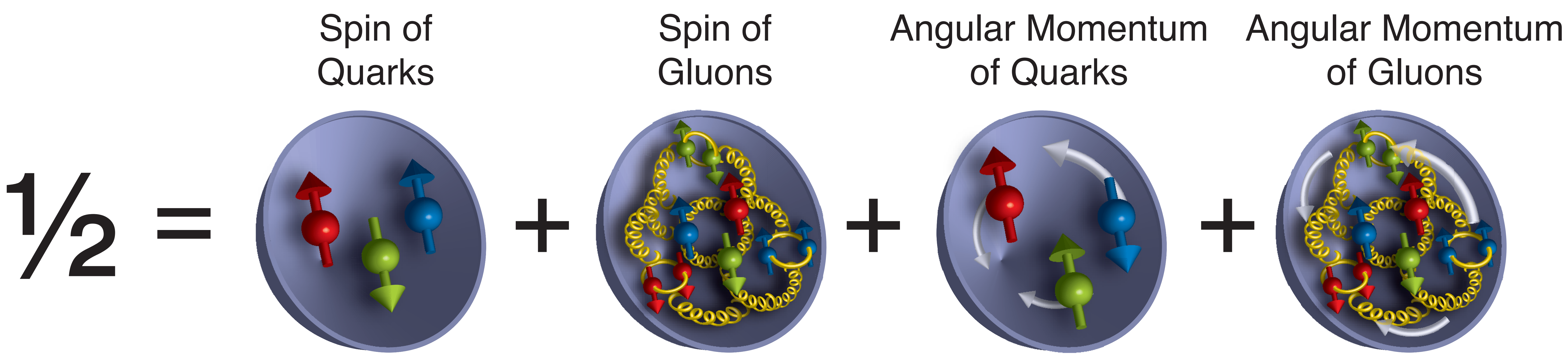
Key Topic in ep: Proton Spin Puzzle

What are the appropriate degrees of freedom in QCD that would explain "spin" of a proton?

- After 20 years effort
  - Quarks (valence and sea): ~30% of proton spin in limited range
  - Gluons (latest RHIC data): ~20% of proton spin in limited range
  - Where is the rest?



It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons



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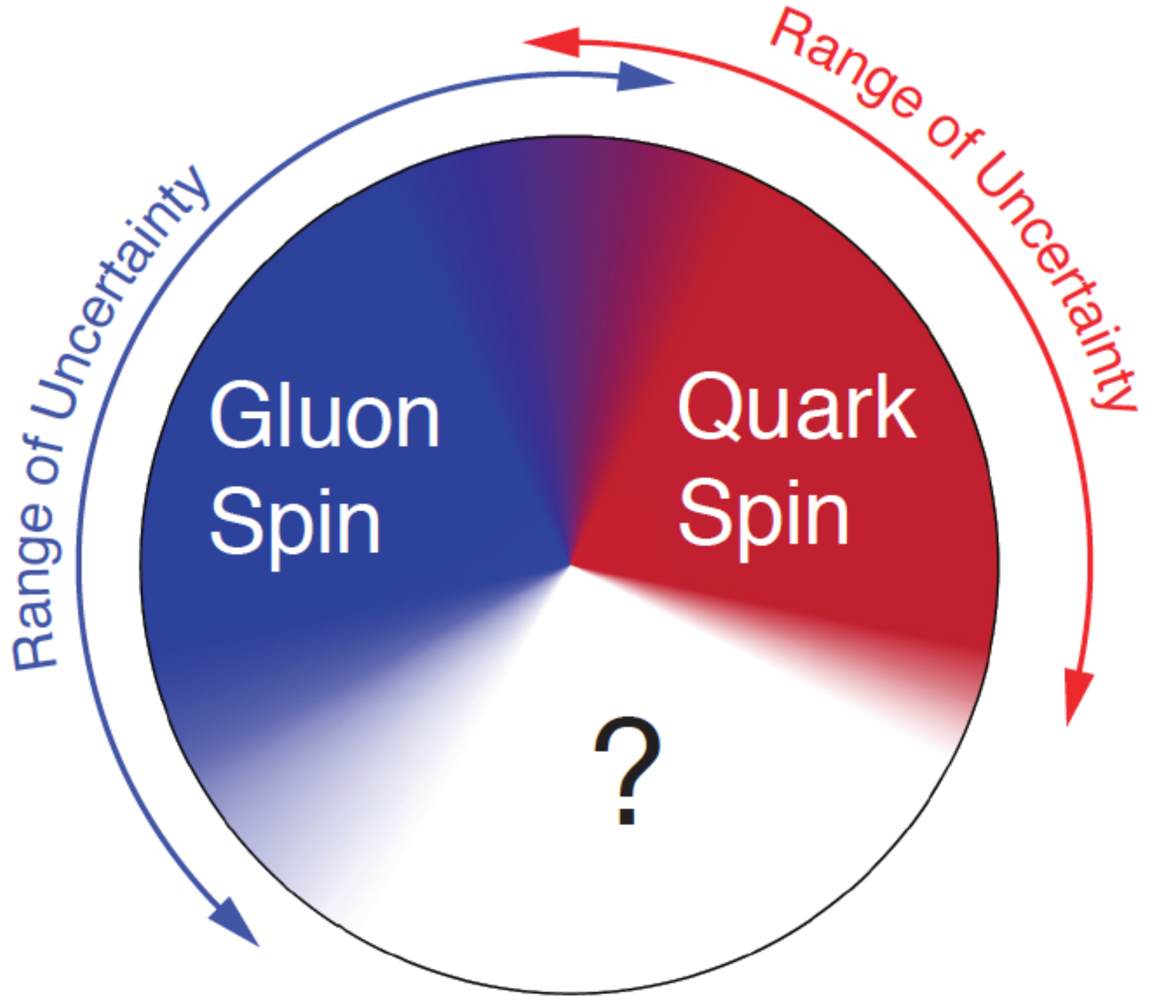
  - Gluons (latest RHIC data): ~20% of proton spin in limited range
  - Where is the rest?



It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons

Jaffe-Manohar sum rule:

$$\frac{1}{2} = \frac{1}{2}\int_0^1 \mathrm{d}x \Delta\Sigma(x, Q^2) + \int_0^1 \mathrm{d}x \Delta g(x, Q^2) + \sum_q L_q + L_g$$

What Does a Proton Look Like?

- In transverse momentum?
- In transverse space?
- How are these distributions correlated with overall nucleon properties, such as spin direction?

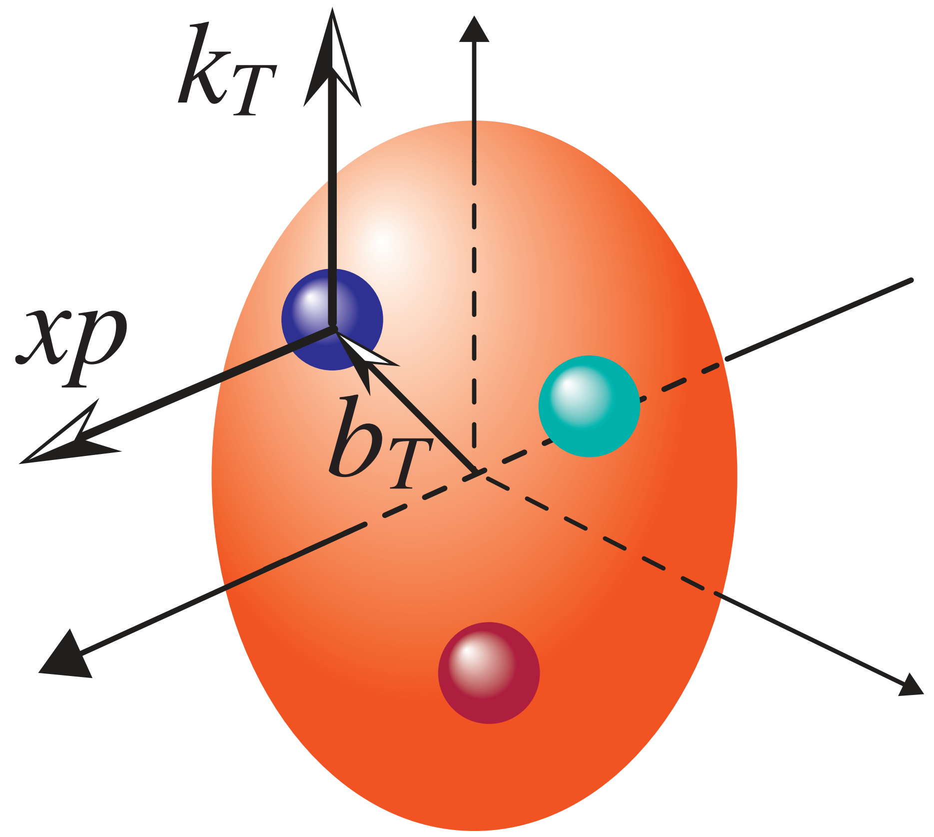
What Does a Proton Look Like?

- In transverse momentum?
- In transverse space?
- How are these distributions correlated with overall nucleon properties, such as spin direction?

3D Imaging

More Detail: 3-D Imaging of Quarks and Gluons

$W(x, b_T, k_T)$



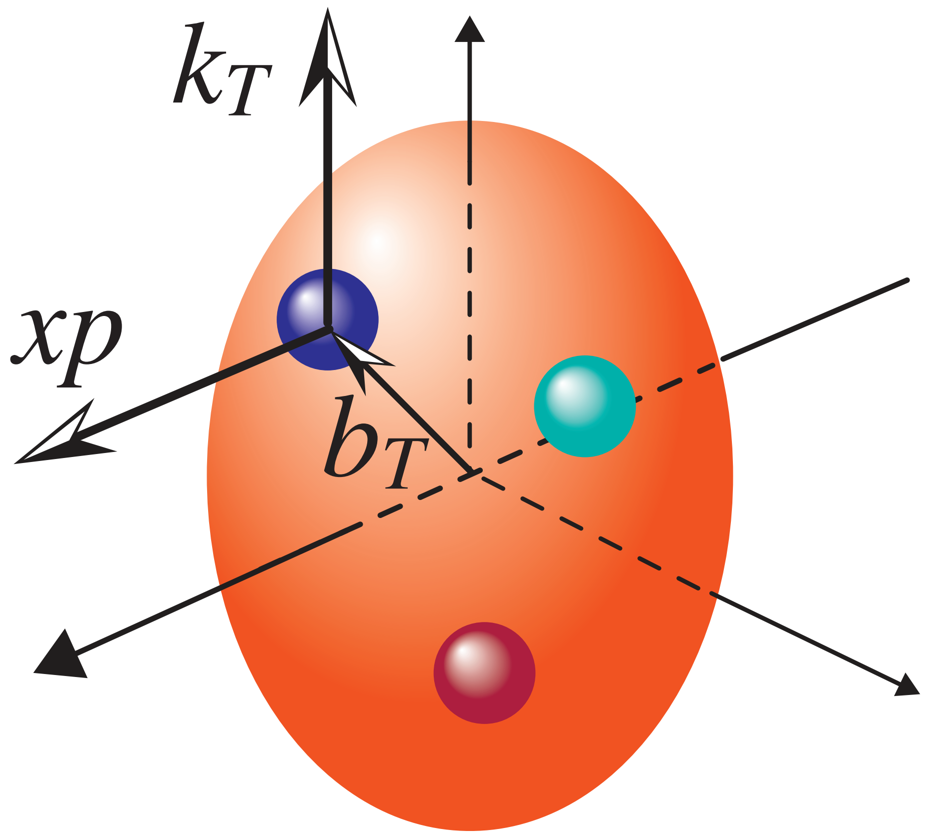
Mother of all functions describing the structure of the proton:

5D Wigner Function: $W(x, k_T, b_T)$

Was considered not measurable.
Recent efforts indicate opportunities via dijet measurements

More Detail: 3-D Imaging of Quarks and Gluons

$W(x,b_T,k_T)$



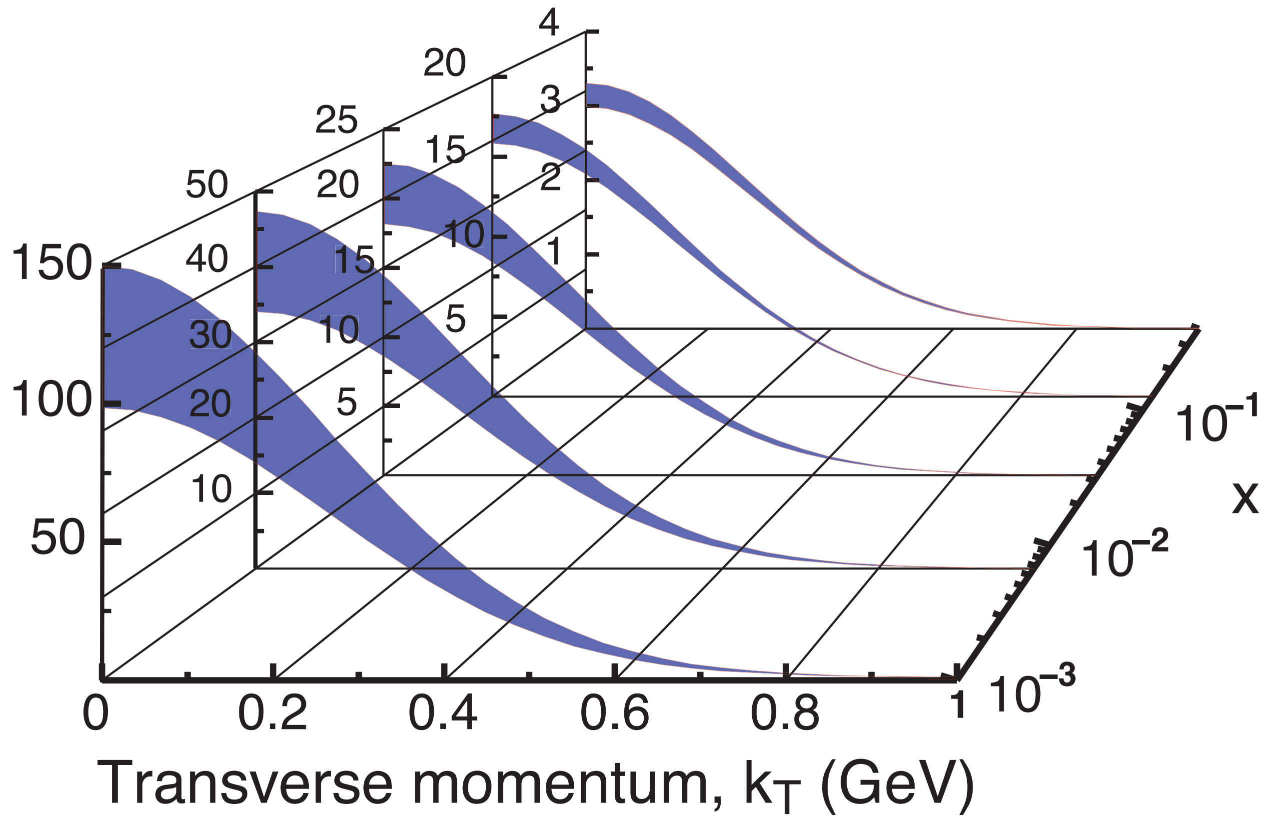
More Detail: 3-D Imaging of Quarks and Gluons

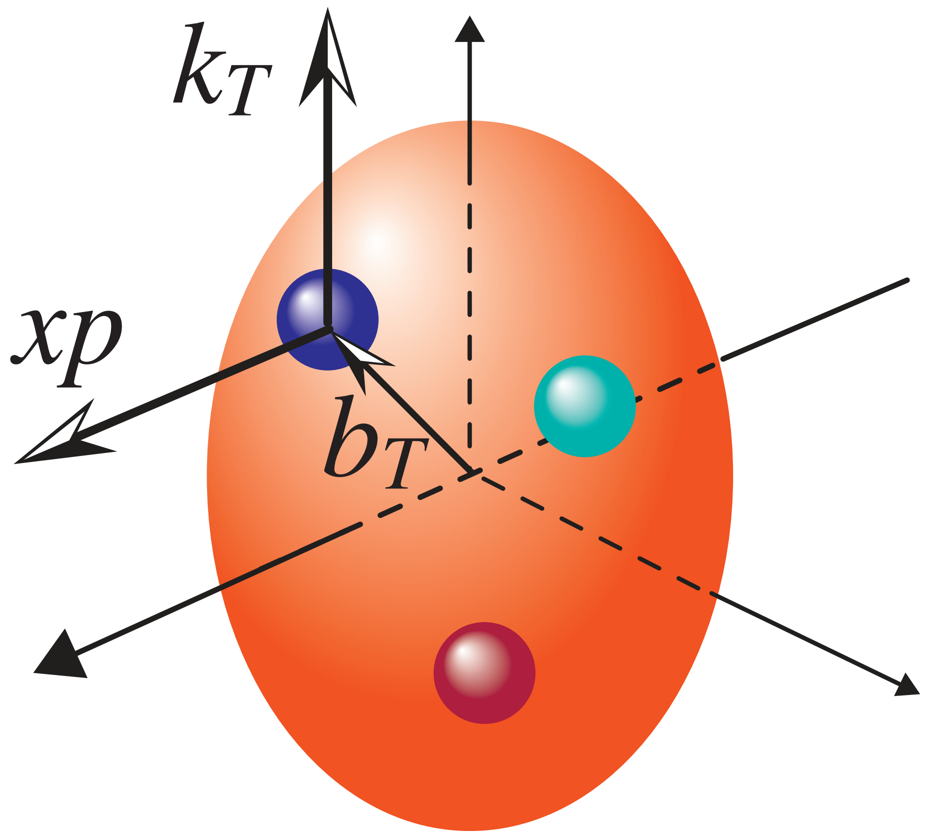
Momentum space

$W(x,b_T,k_T)$

$\int d^2b_T$

$f(x,k_T)$





Spin-dependent transverse dependent PDF

Transverse Momentum Distributions (TMDs)

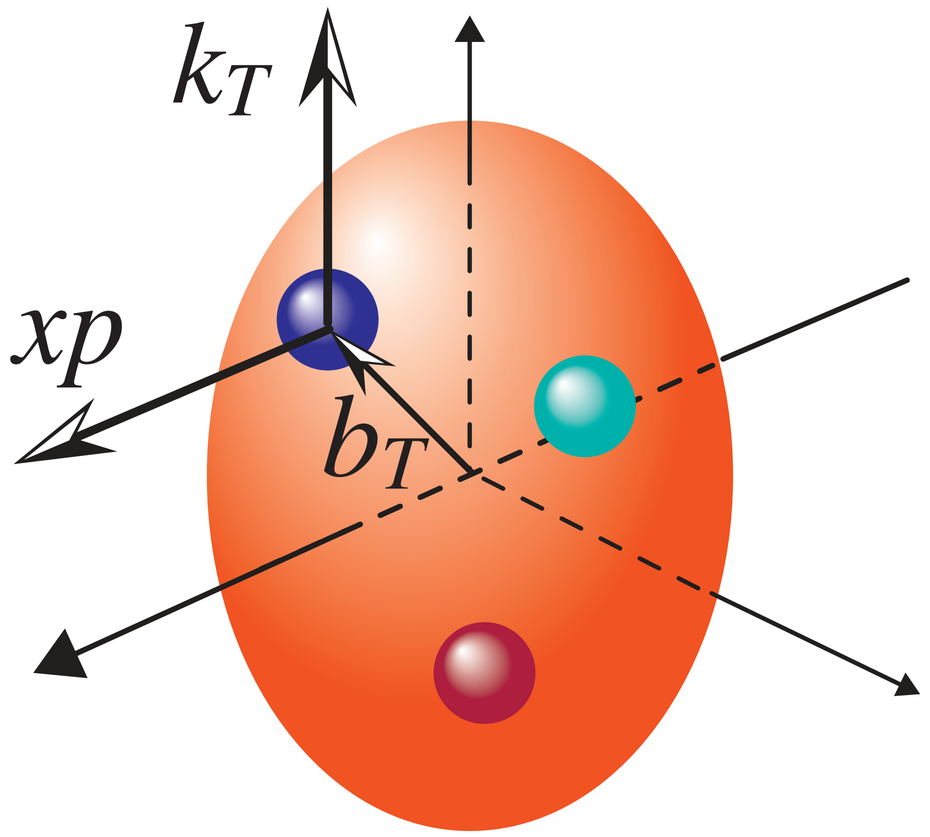
More Detail: 3-D Imaging of Quarks and Gluons

Momentum space

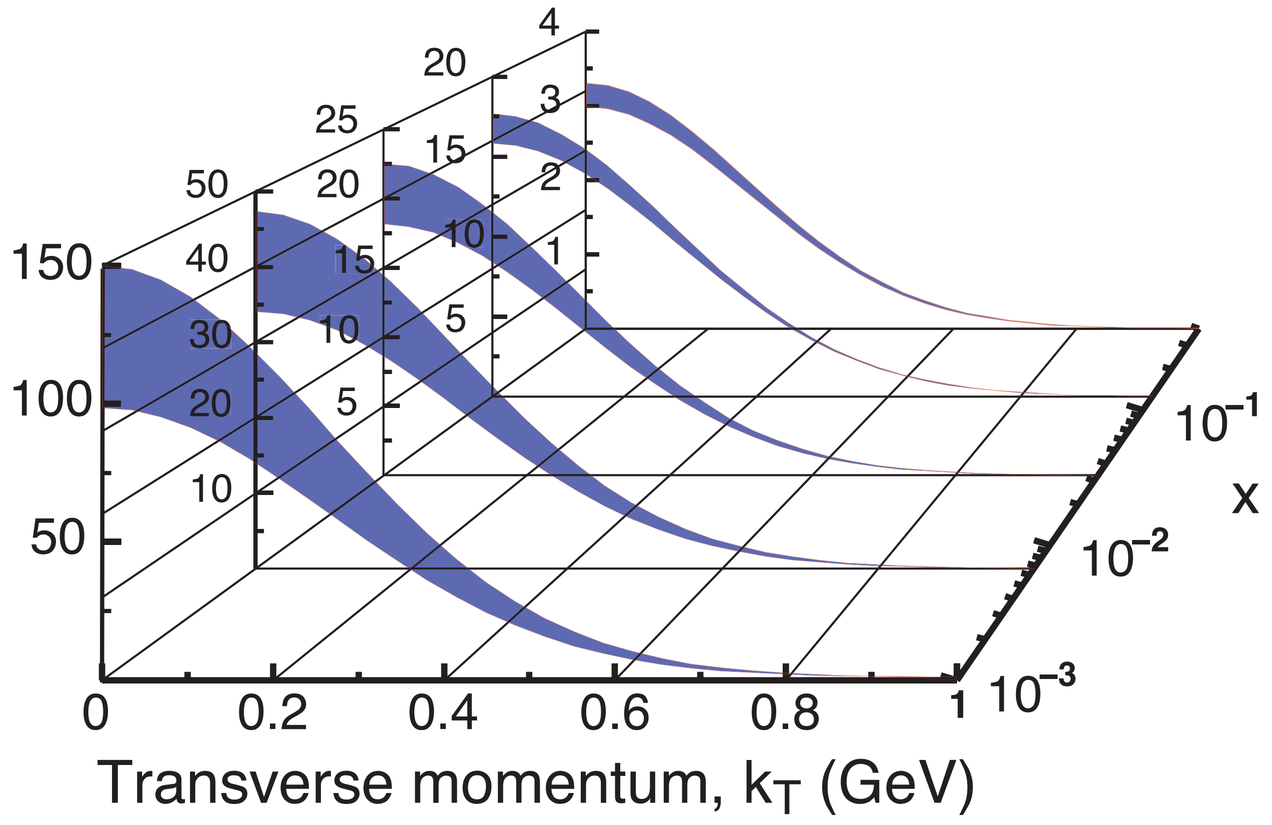
$W(x, b_T, k_T)$

Coordinate space

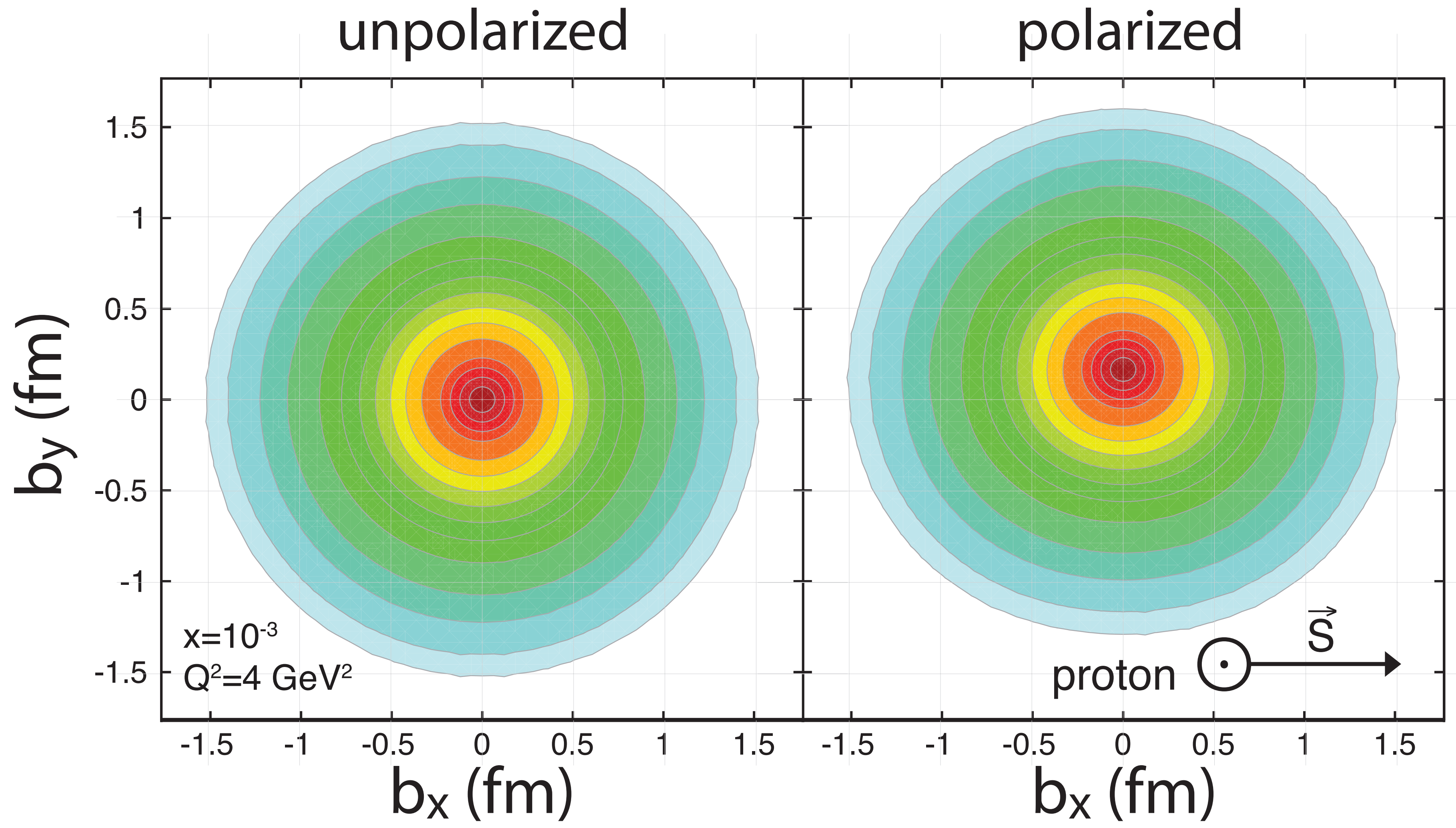
$\int d^2b_T$ $\qquad$ $\int d^2k_T$



$f(x, k_T)$ $\qquad$ $f(x, b_T)$



Spin-dependent transverse dependent PDF



Spin and impact parameter dependent PDF

Transverse Momentum Distributions (TMDs)

More Detail: 3-D Imaging of Quarks and Gluons

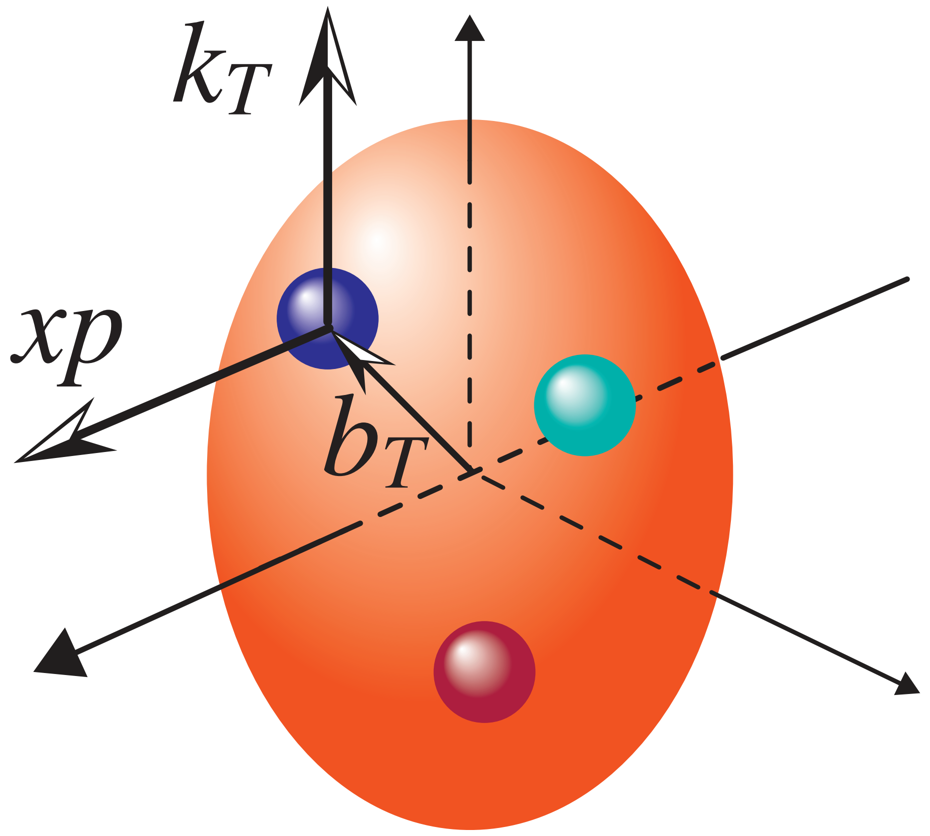
Momentum space

$W(x, b_T, k_T)$

Coordinate space

$\int d^2 b_T$

$\int d^2 k_T$



$f(x, k_T)$

$f(x, b_T)$

More Detail: 3-D Imaging of Quarks and Gluons

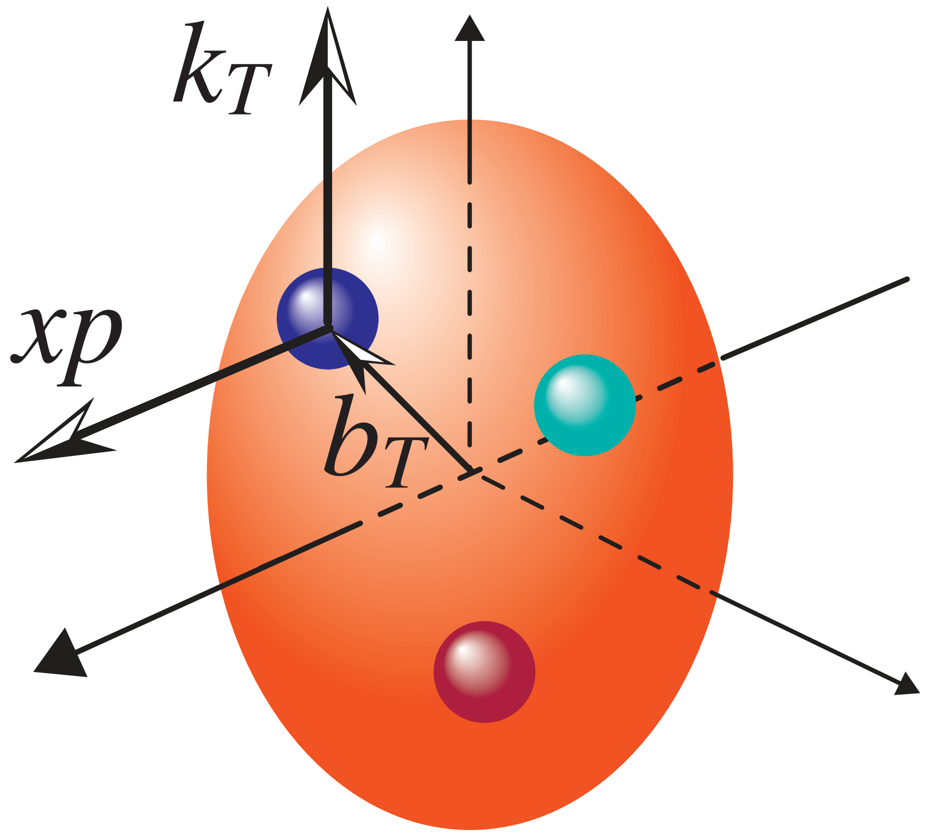
Momentum space

Coordinate space

$W(x, b_T, k_T)$

$\int d^2b_T$

$\int d^2k_T$



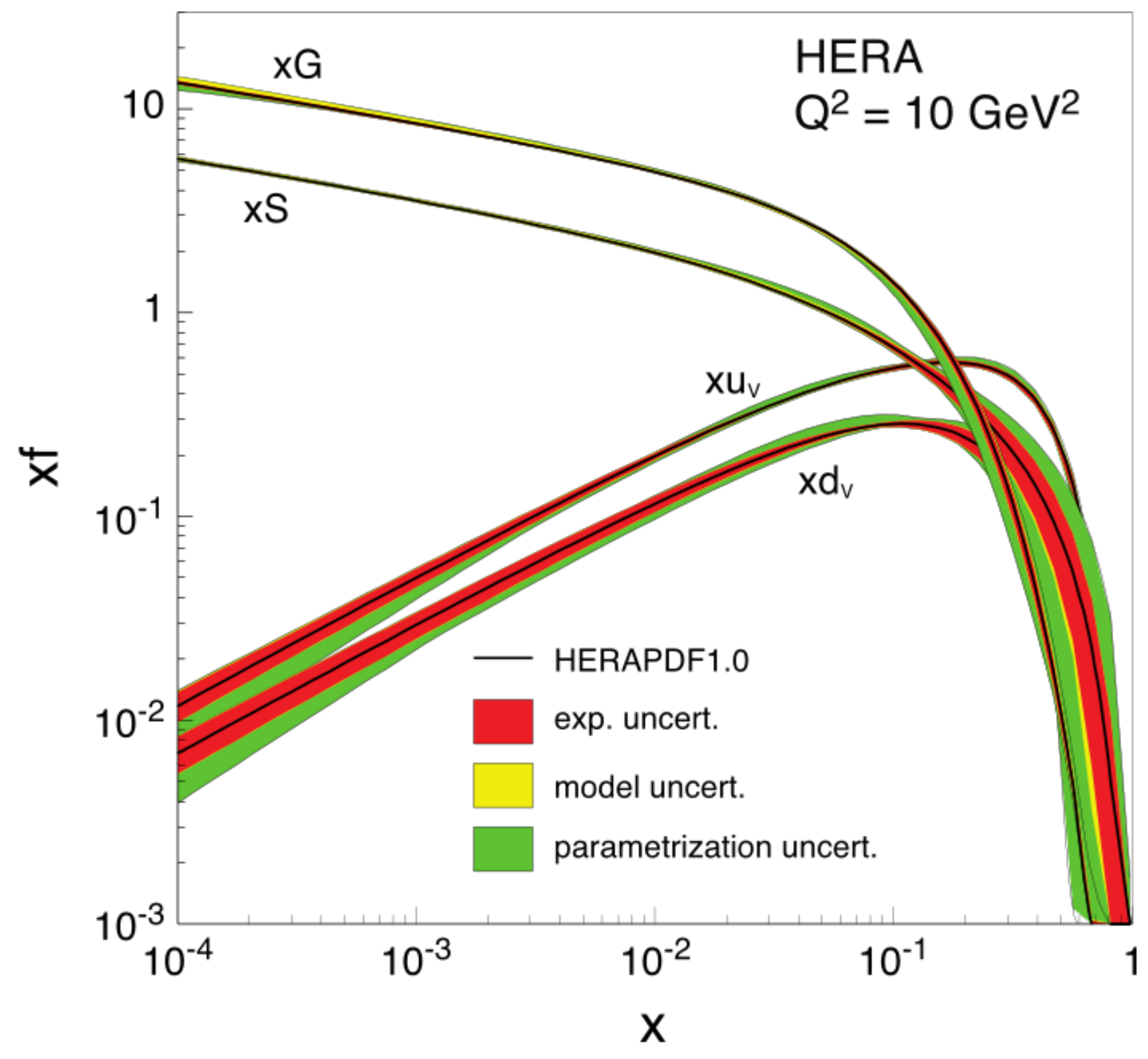
$f(x, k_T)$

$f(x, b_T)$

$\int d^2k_T$

$\int d^2b_T$

$f(x)$



Parton densities

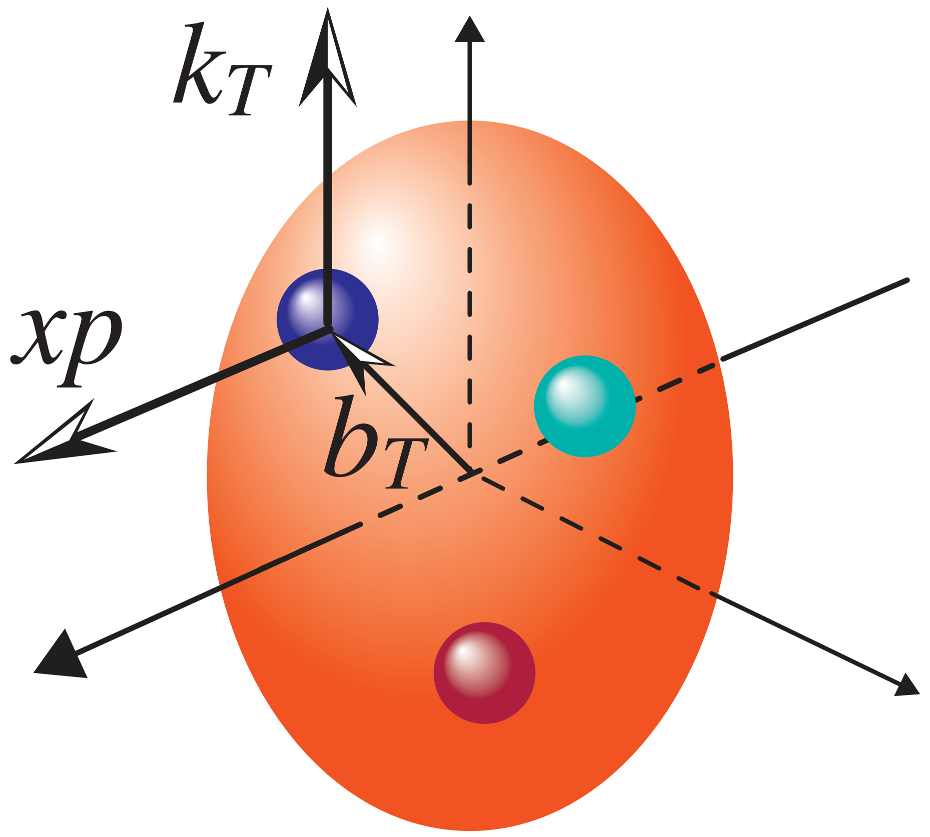
More Detail: 3-D Imaging of Quarks and Gluons

Momentum space

$W(x,b_T,k_T)$

Coordinate space

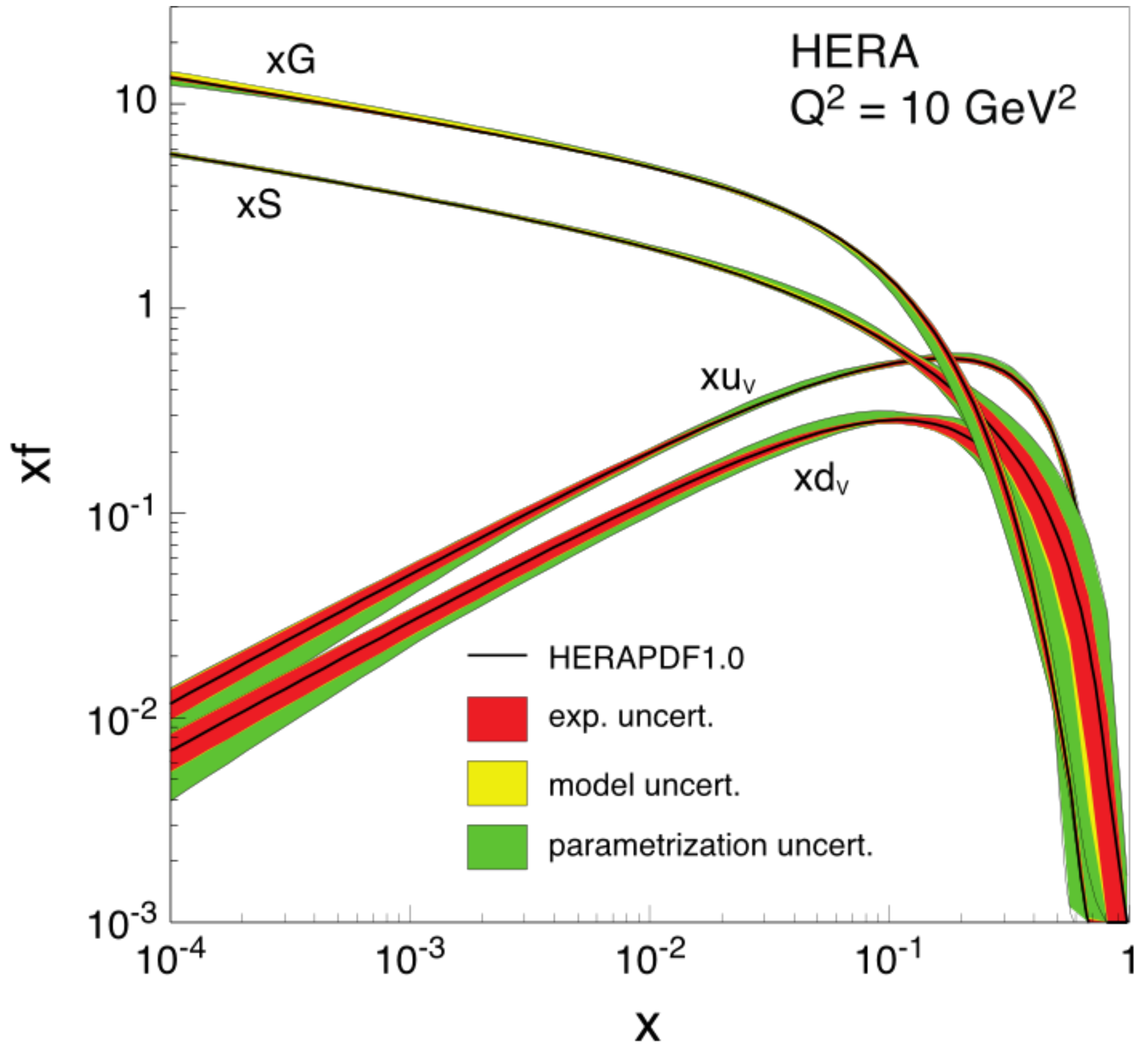
$\int d^2b_T$ $\int d^2k_T$



$f(x,k_T)$ $f(x,b_T)$

$\int d^2k_T$ $\int d^2b_T$

$f(x)$

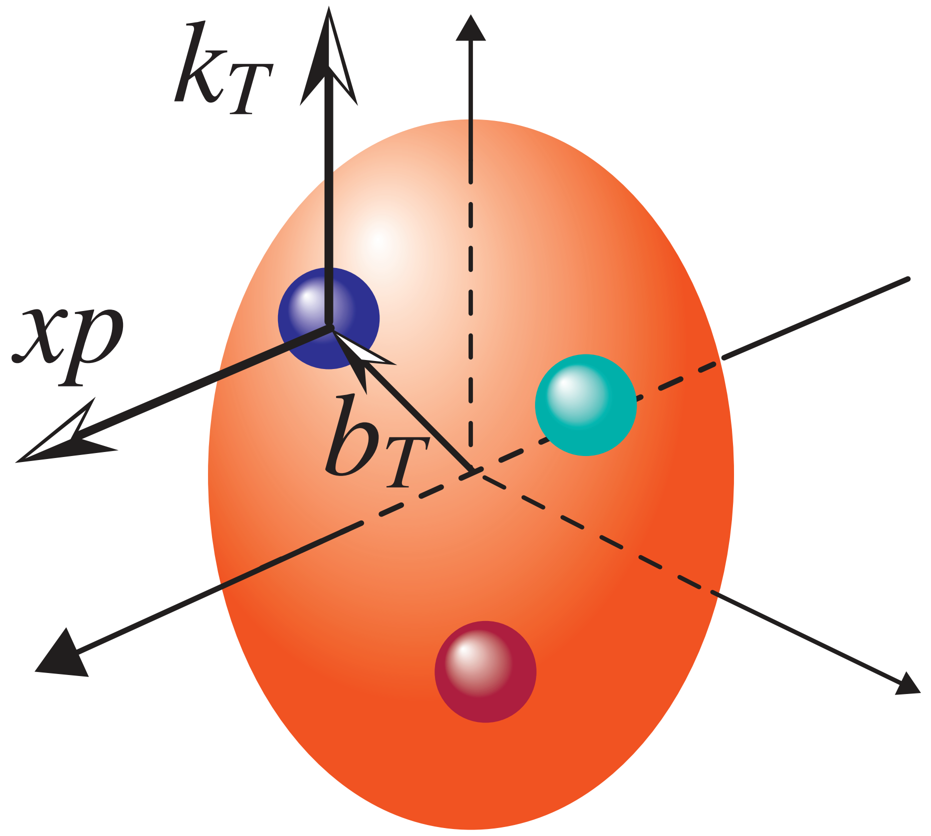


Parton densities

More Detail: 3-D Imaging of Quarks and Gluons

$W(x, b_T, k_T)$

Coordinate space

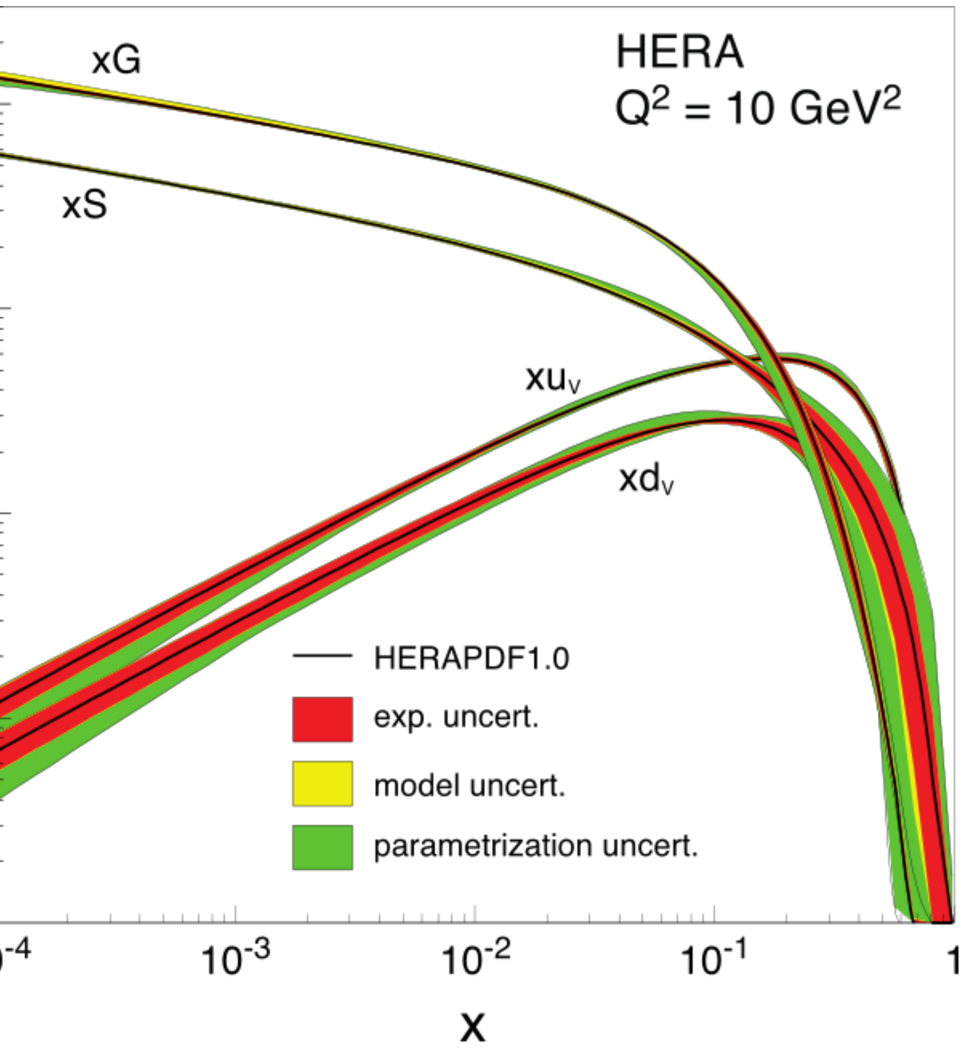


$\int d^2k_T$

$f(x, b_T)$

$\int d^2b_T$

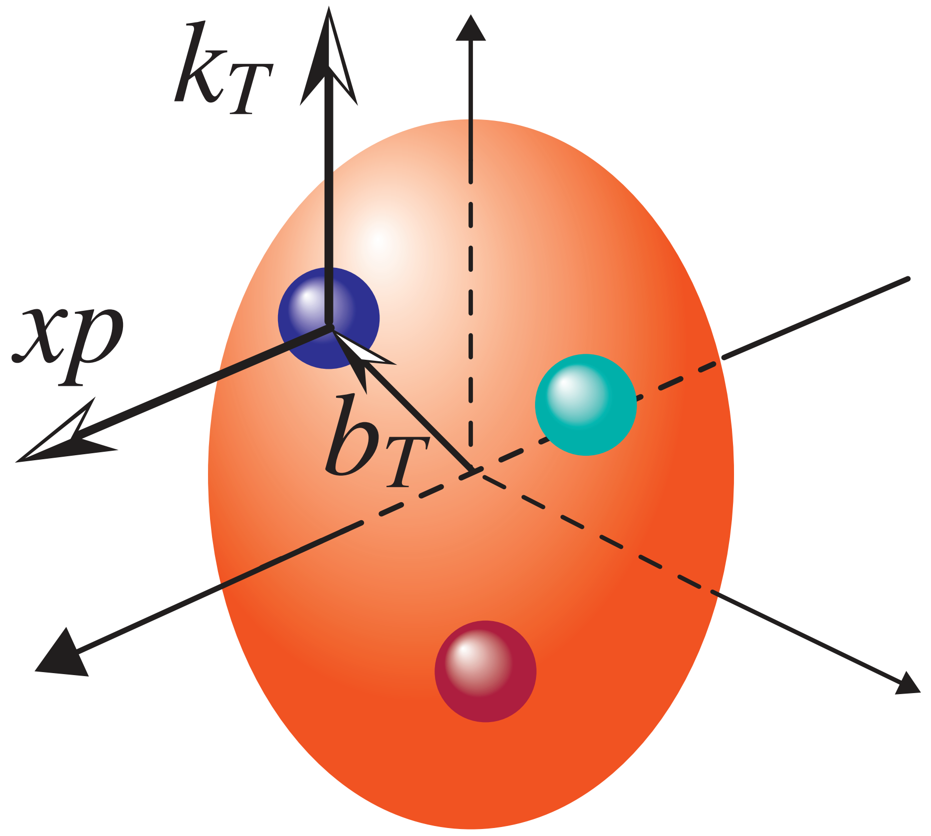
$f(x)$



Parton densities

More Detail: 3-D Imaging of Quarks and Gluons

$W(x, b_T, k_T)$



$\int d^2k_T$

Coordinate space

$f(x, b_T)$

$b_T \longleftrightarrow t$

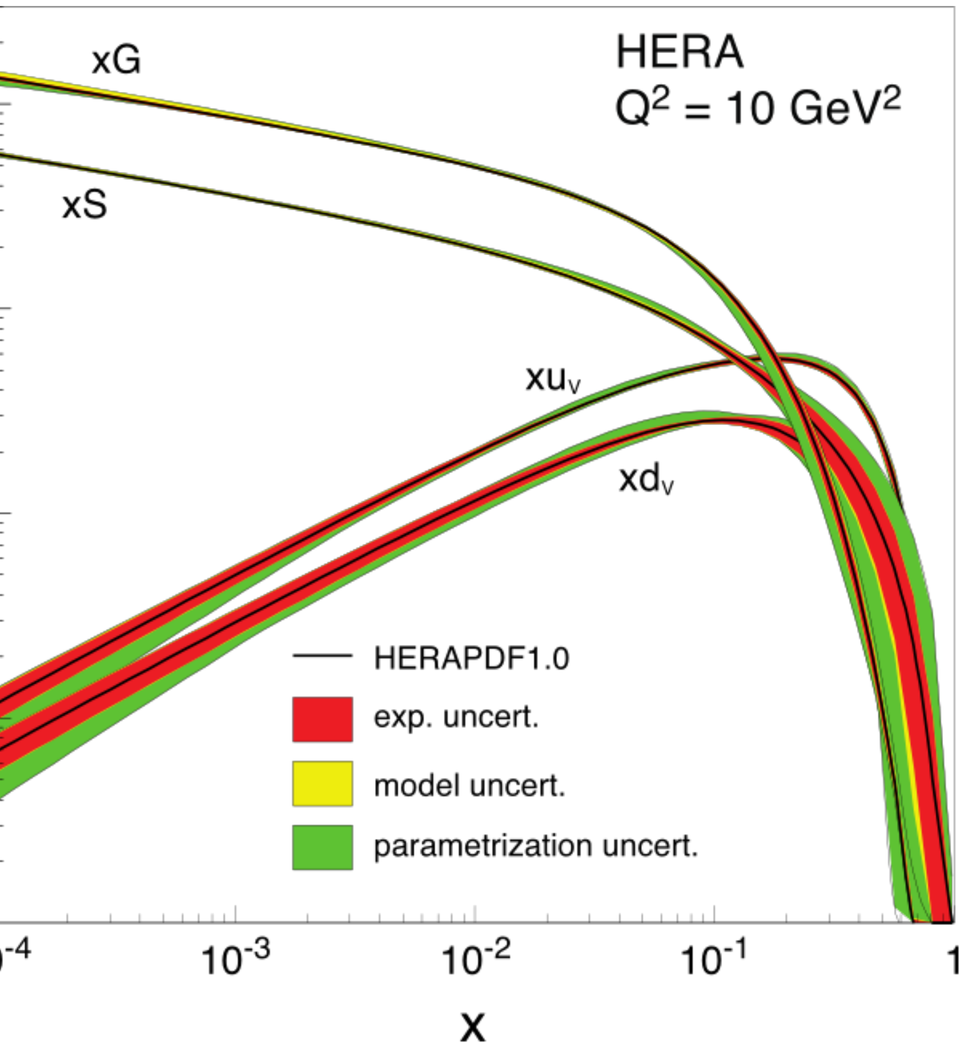
Fourier

$H(x, 0, t)$

$\int d^2b_T$

$\int dx$

$f(x)$



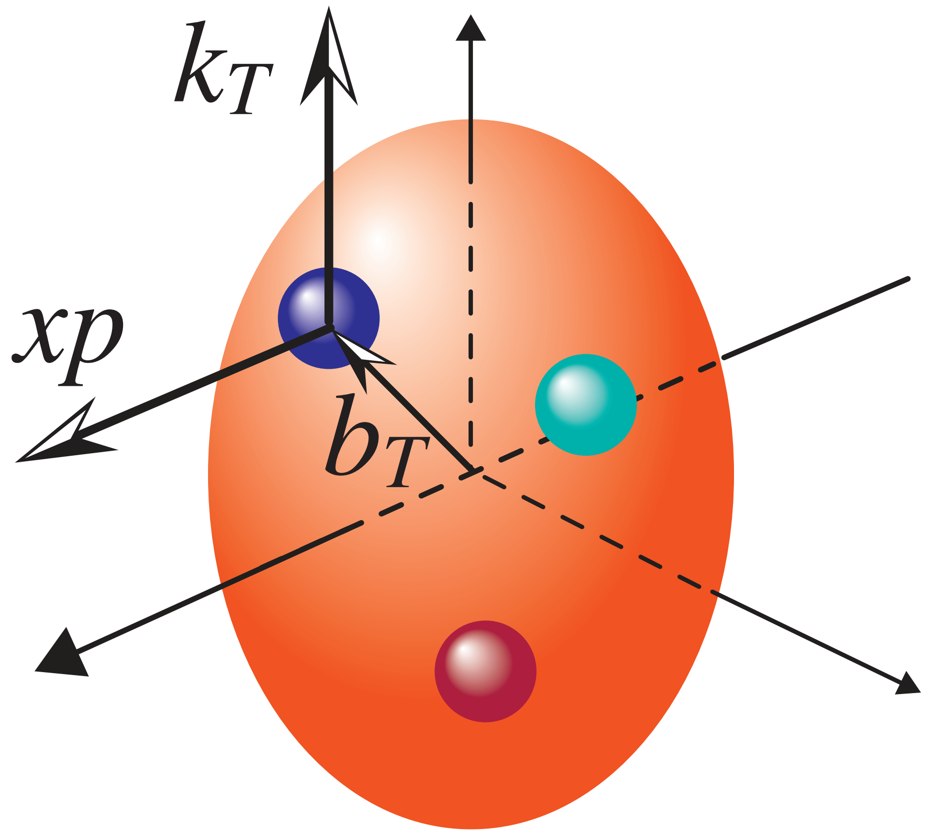
Parton densities

$F(t)$

Form factor

More Detail: 3-D Imaging of Quarks and Gluons

$W(x,b_T,k_T)$



$\int d^2k_T$

Coordinate space

$f(x,b_T)$

$b_T \longleftrightarrow t$

Fourier

$H(x, 0, t)$

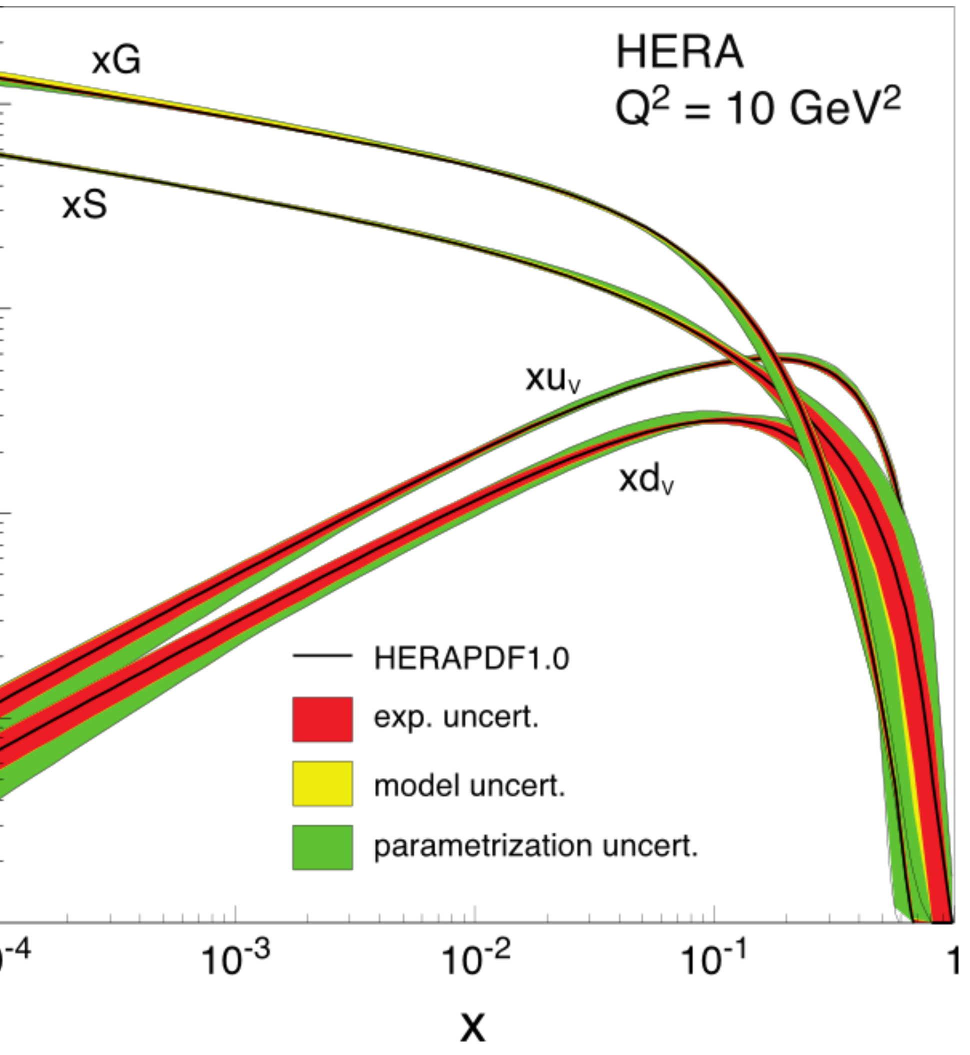
$H(x, \xi, t)$

Generalized
Parton
Distribution
GPD

$\int d^2b_T$

$\int dx$

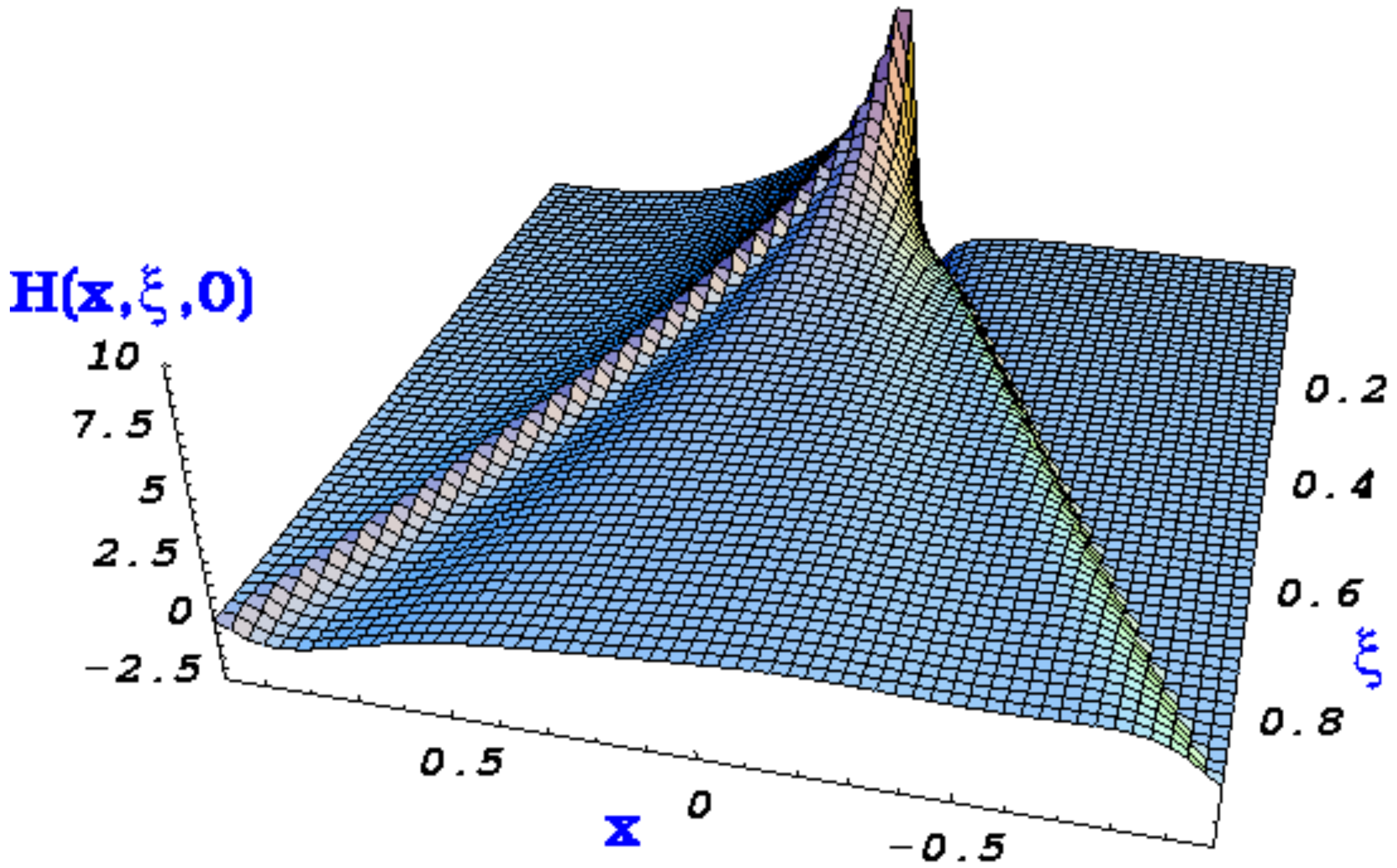
$f(x)$



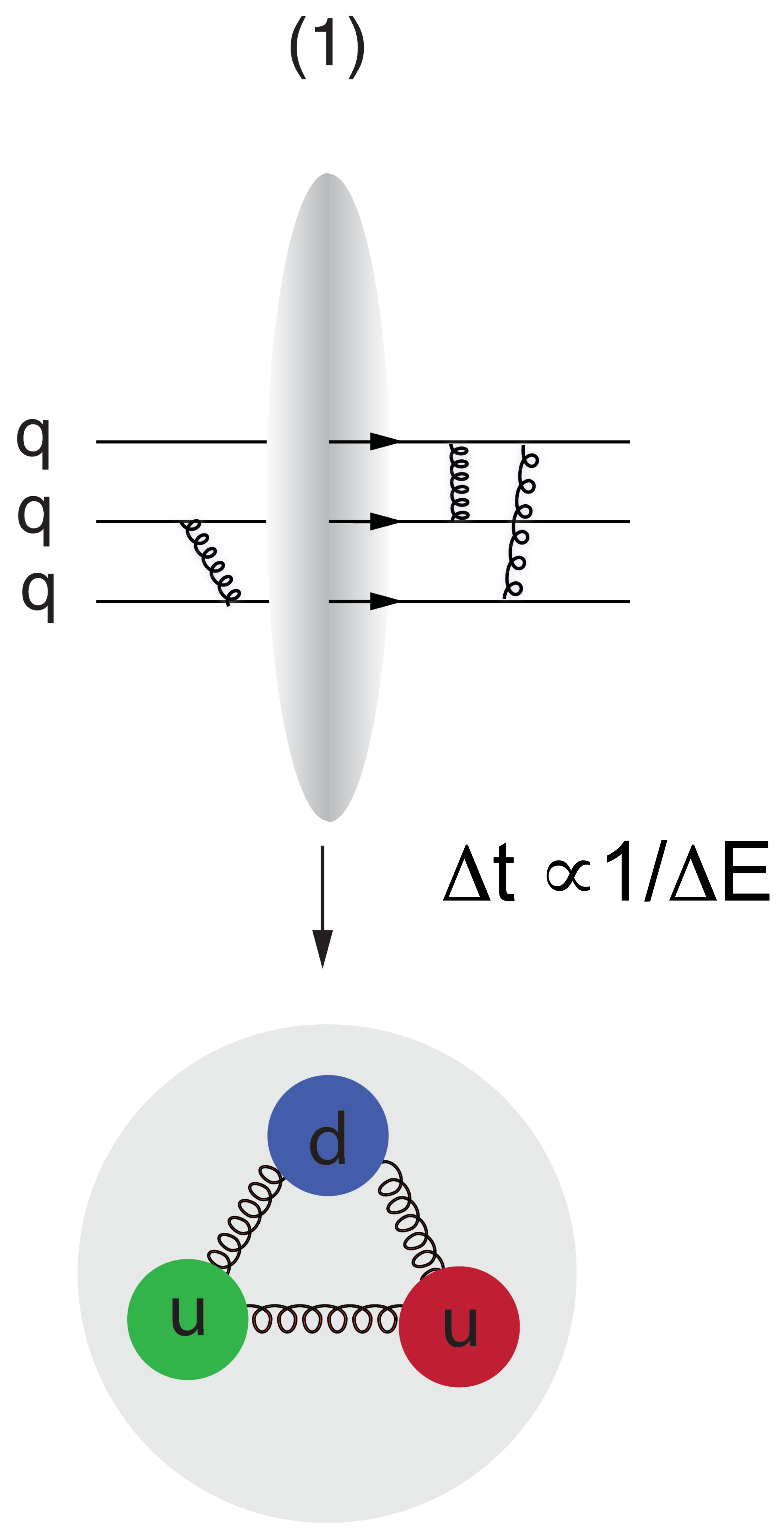
Parton densities

$F(t)$

Form factor



A Look Inside the Boosted Proton



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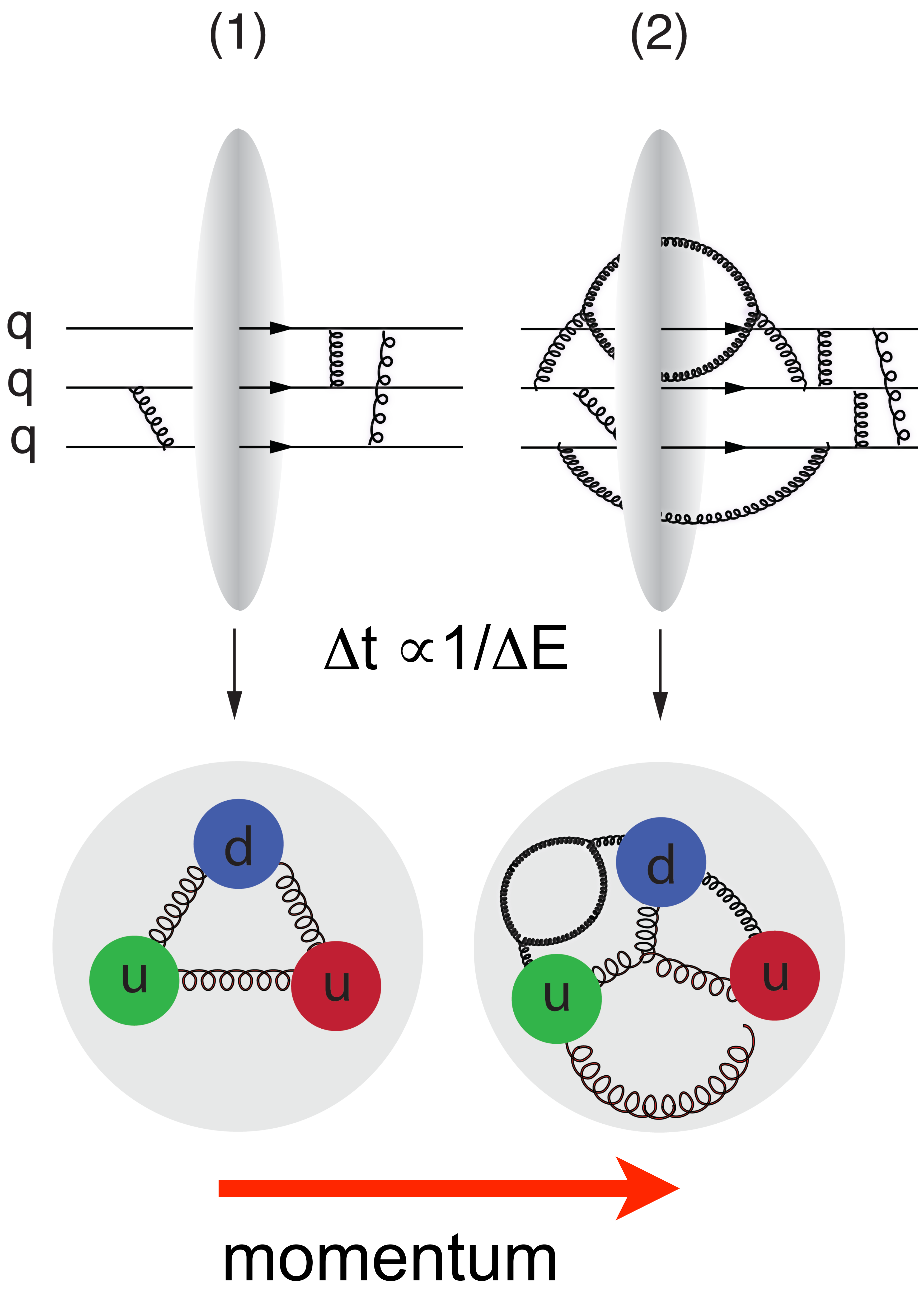
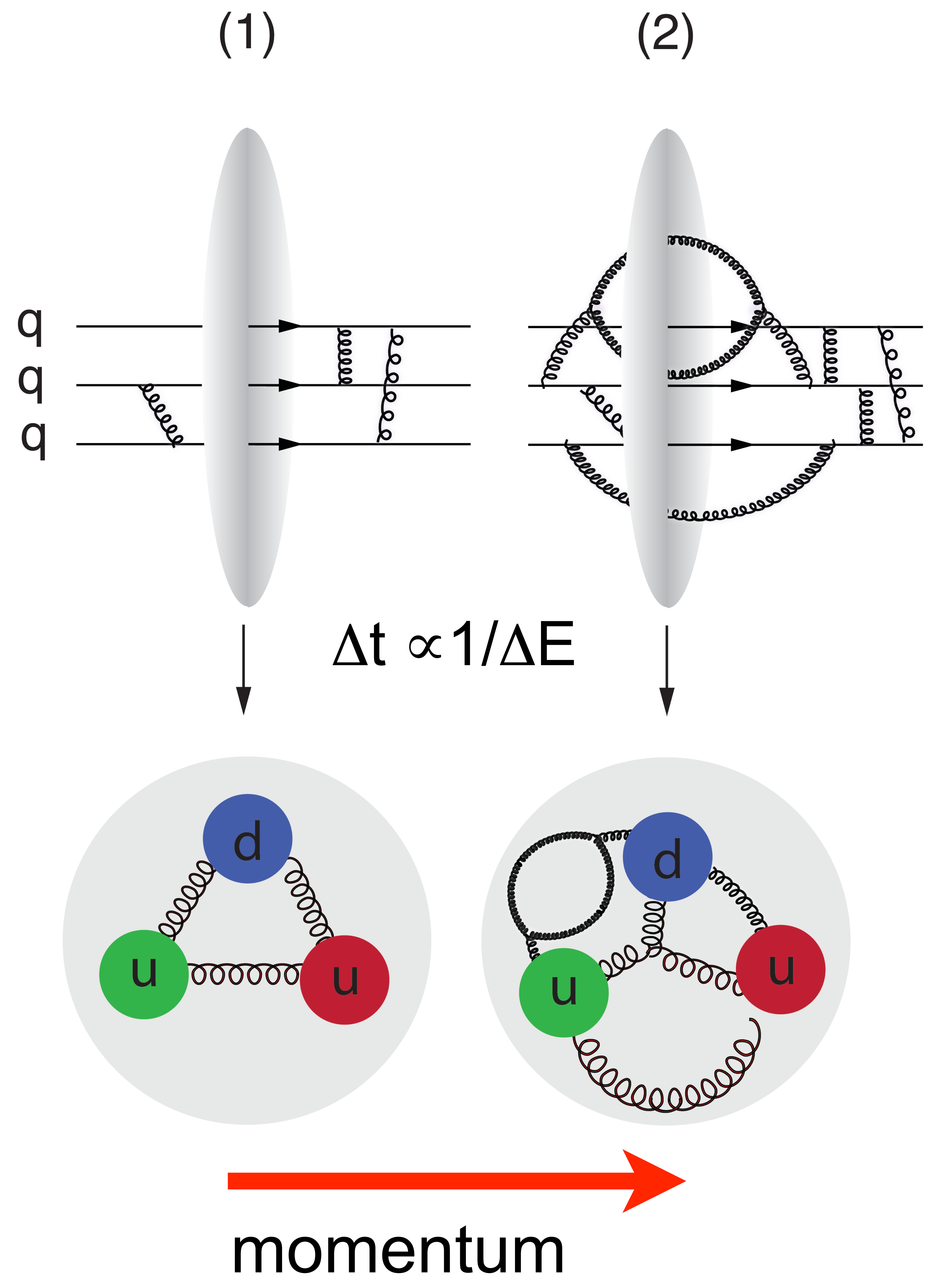


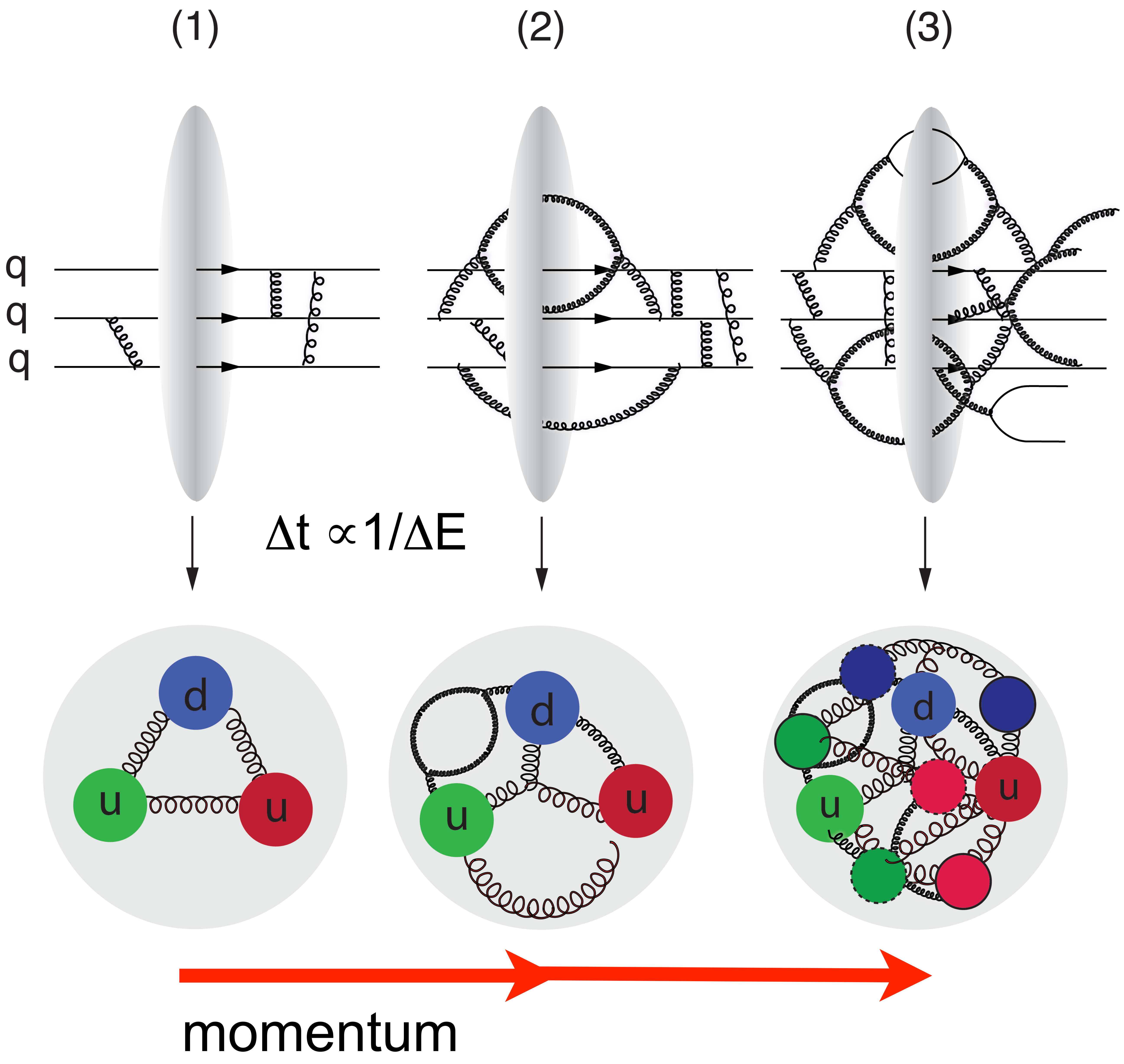
A Look Inside the Boosted Proton



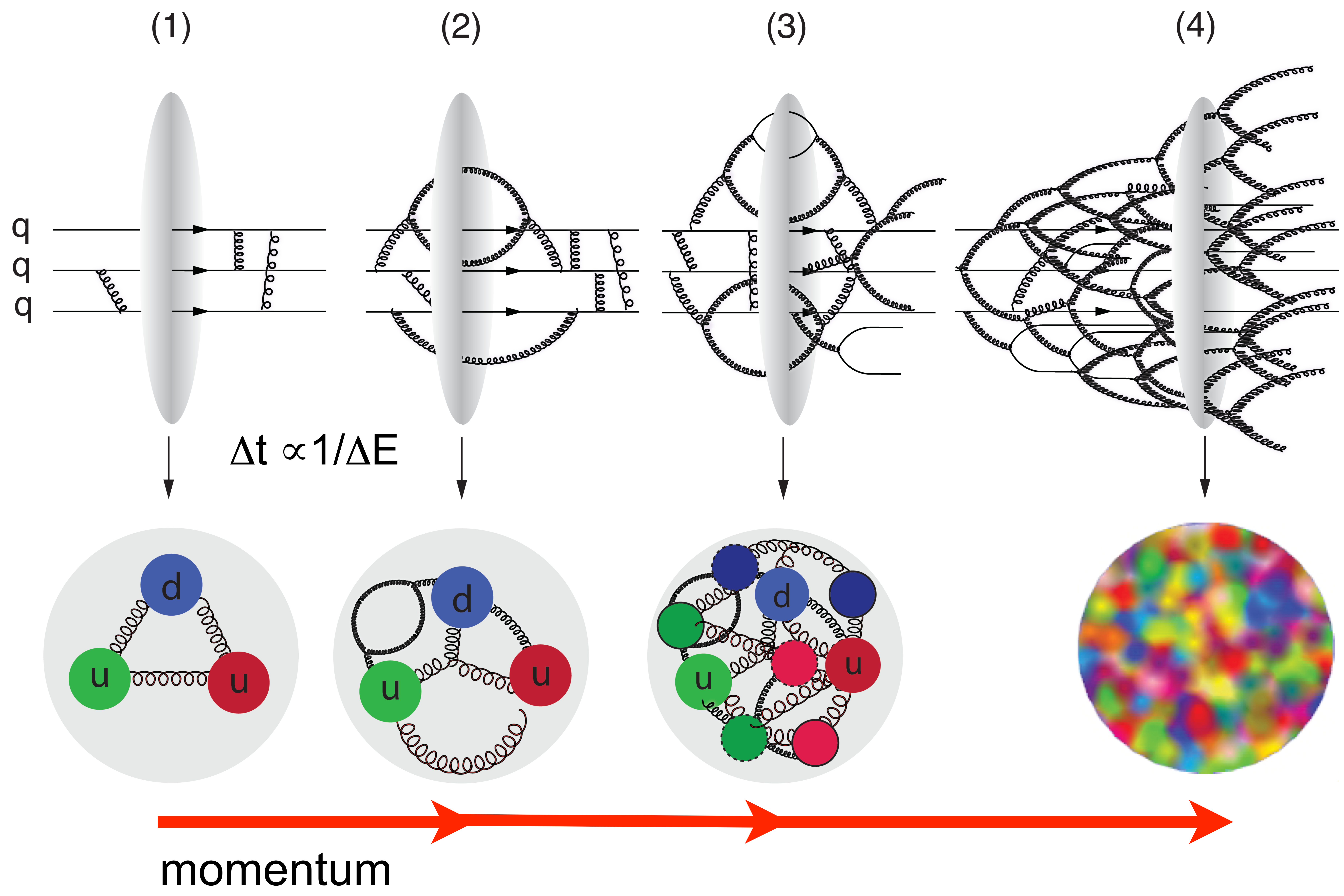
In QCD, the proton is made up of quanta that fluctuate in and out of existence

- Boosted proton:
  - Fluctuations time dilated on strong interaction time scales
  - Long lived gluons can radiate further small x gluons…
  - Explosion of gluon density

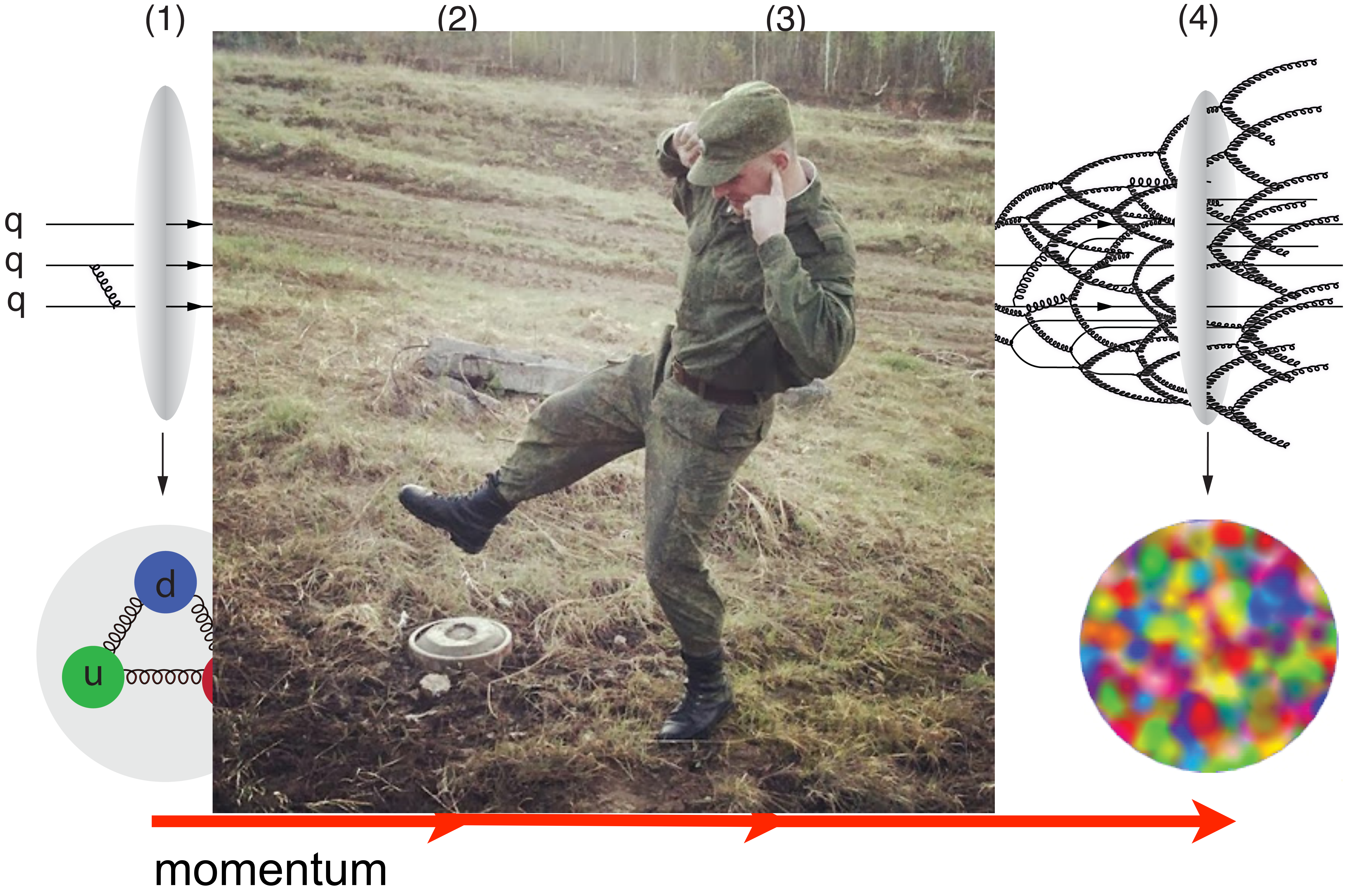
A Look Inside the Boosted Proton



A Look Inside the Boosted Proton



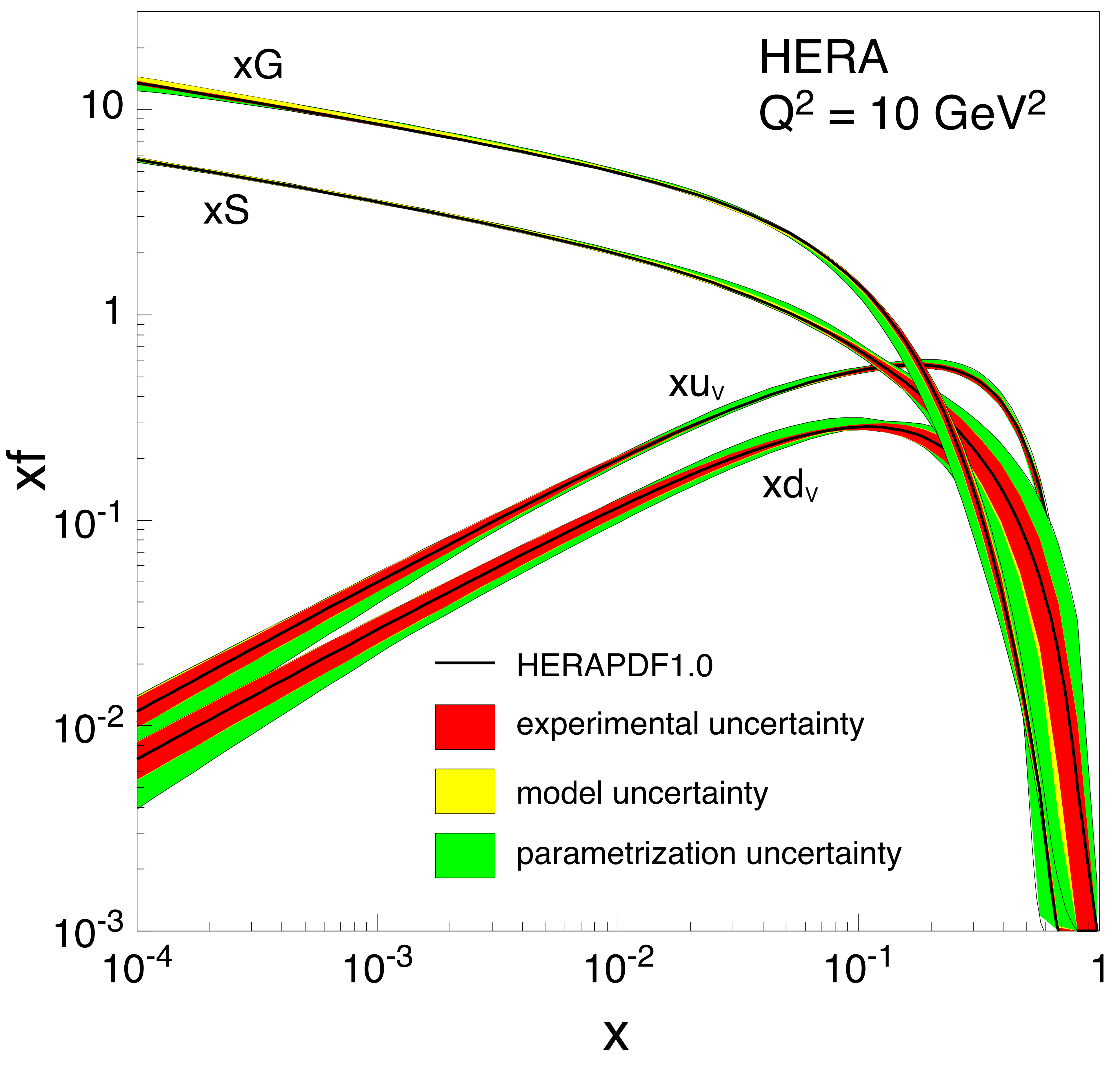
A Look Inside the Boosted Proton



Issues with our Current Understanding

Ever growing $G(x,Q^2)$?

- Linear DGLAP Evolution Scheme
  - built in high energy "catastrophe"
  - G rapid rise violates unitary bound
- Linear BFKL Evolution Scheme
  - Density along with σ grows as a power of energy
  - Can densities & σ rise forever?
  - Black disk limit: $\sigma_{total} \leq 2 \pi R^2$



Something's wrong:
Gluon density is growing too fast
⇒ Must saturate (gluons recombine)
What's the underlying dynamics? Need New Approach

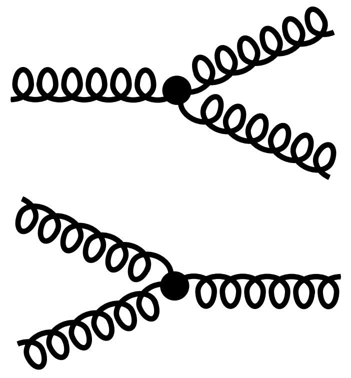
New Approach

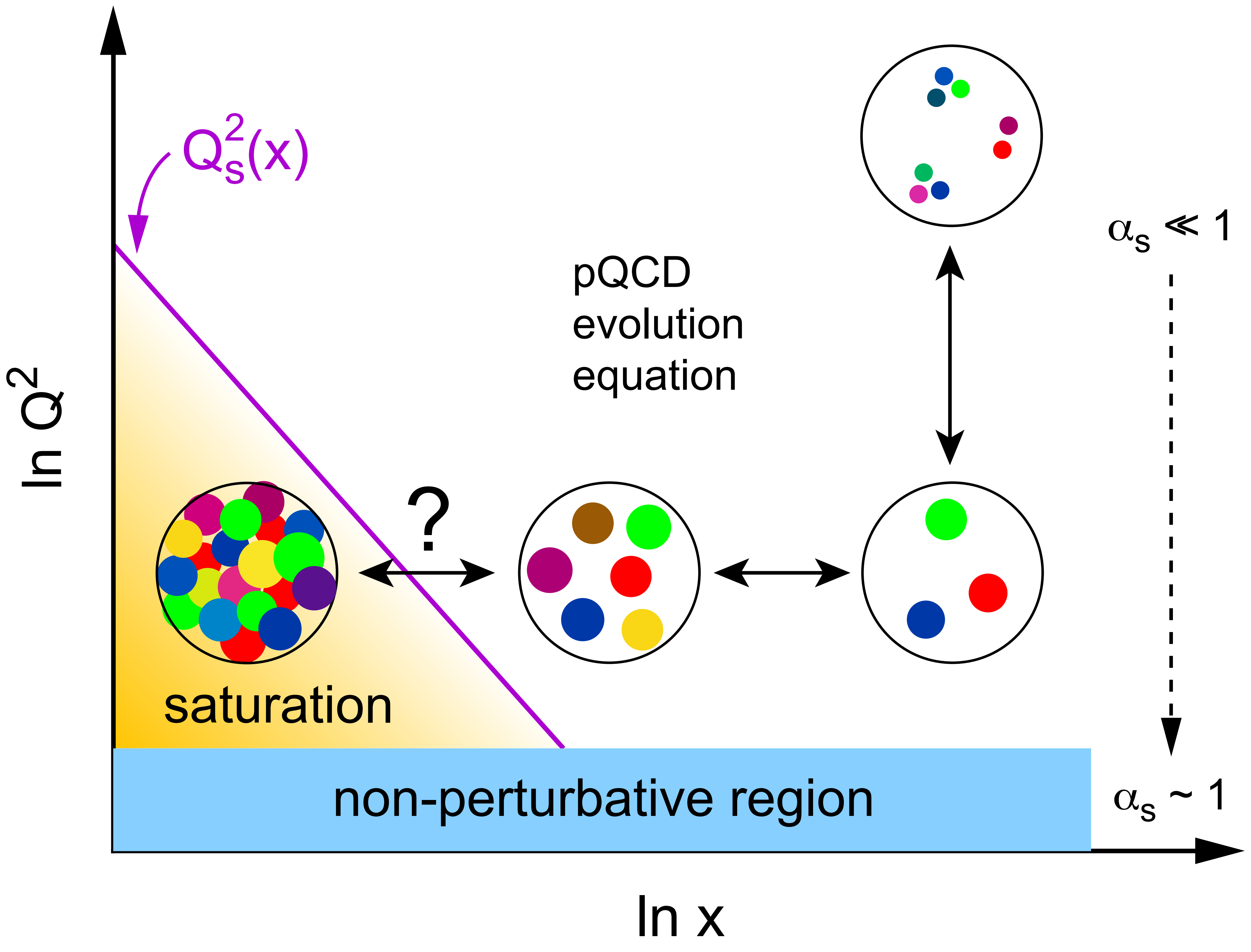
New Approach: Non-Linear Evolution:

- At very high energy: recombination compensates gluon splitting
- Cross sections reach unitarity limit ⇒ saturation
- Needs new evolution equations (JIMWLK/BK)
- Saturation regime characterized by $Q_s(x,A)$

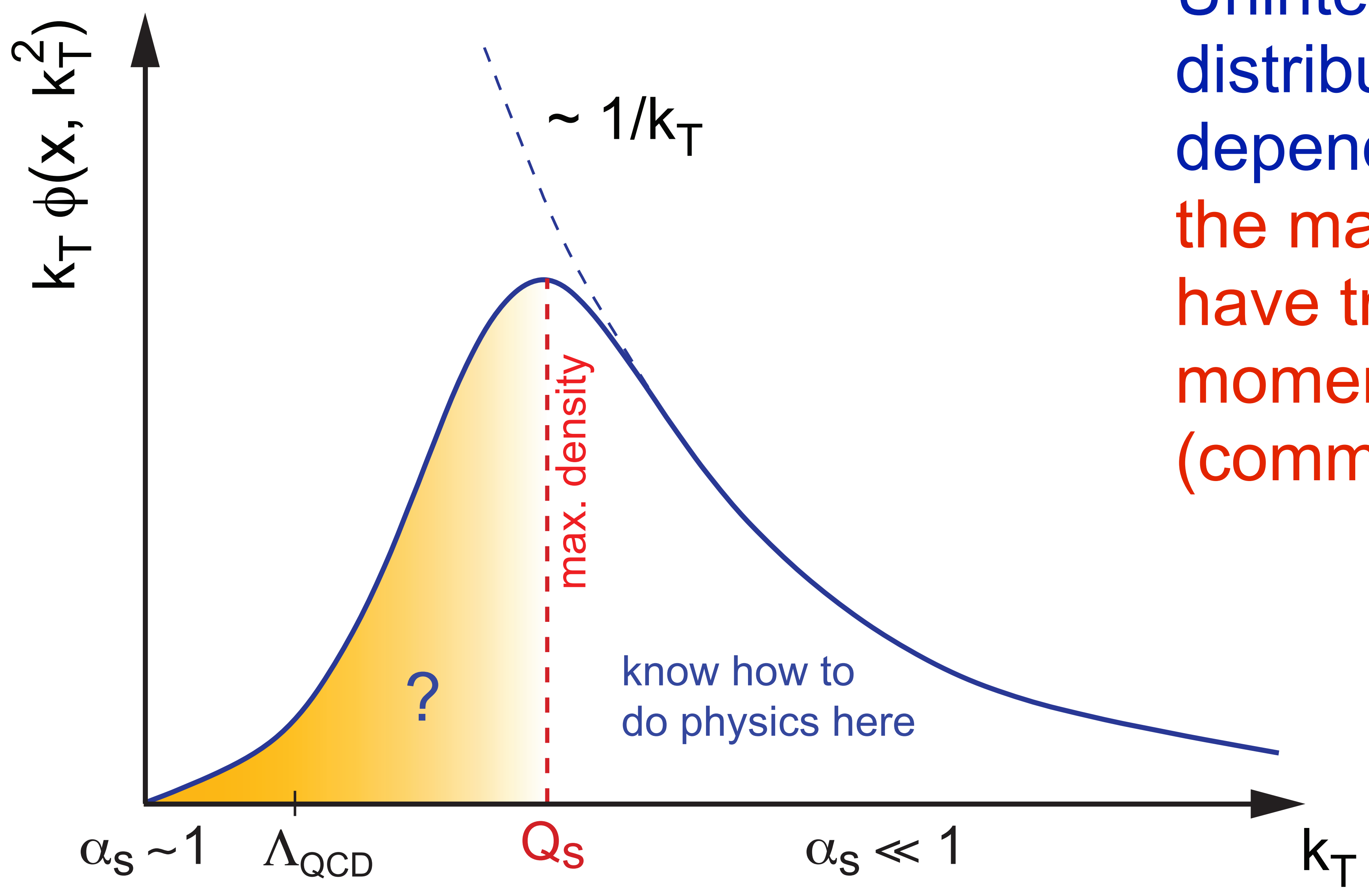
BFKL:

BK adds:





At Q_s: gluon emission balanced by recombination



Unintegrated gluon distribution depends on k_T and x: the majority of gluons have transverse momentum $k_T \sim Q_S$ (common definition)

Color Glass Condensate (CGC)

- The saturated regime is called a Color Glass Condensate
  - "Color" in the name refers to the color charge of quarks and gluons
  - "Glass" is borrowed from the term for silica and other materials that are disordered and act like solids on short time scales but liquids on long time scales. In the CGC the gluons themselves are disordered and do not change their positions rapidly because of time dilation.
  - "Condensate" means that the gluons have a very high density (there is some speculation if the CGC is a BEC)
- The effective theory that describes the CGC is also called the CGC (just to confuse you)
- The CGC evolution equation is called JIMWLK and it's mean field equivalent BK (replacing BFKL)

Nuclear Oomph

Scattering of electrons off nuclei:

Probes interact over distances $L \sim (2m_N x)^{-1}$

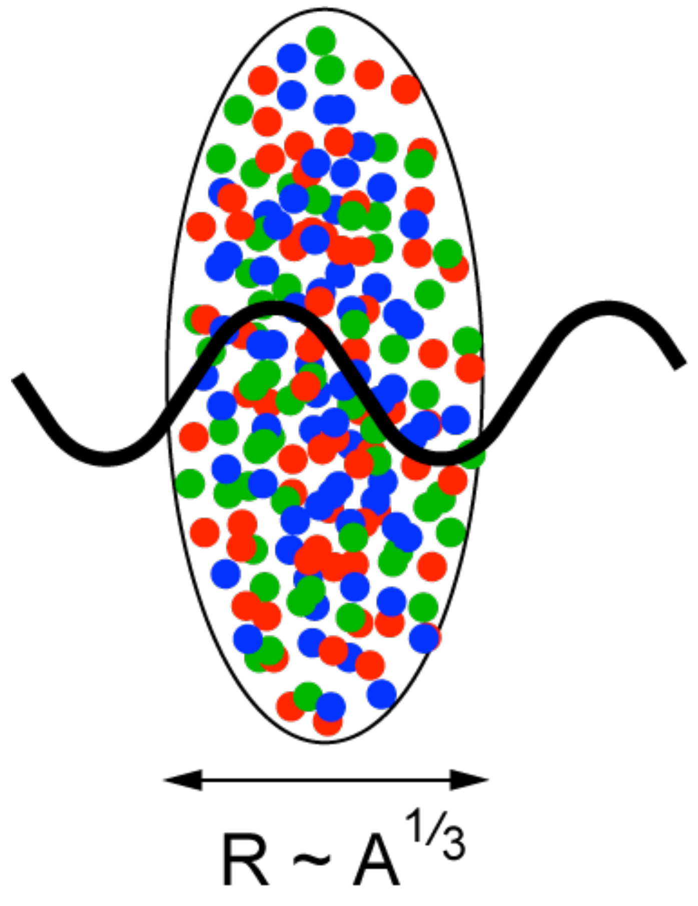
For $L > 2\ R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon

Probe interacts ***coherently*** with all nucleons

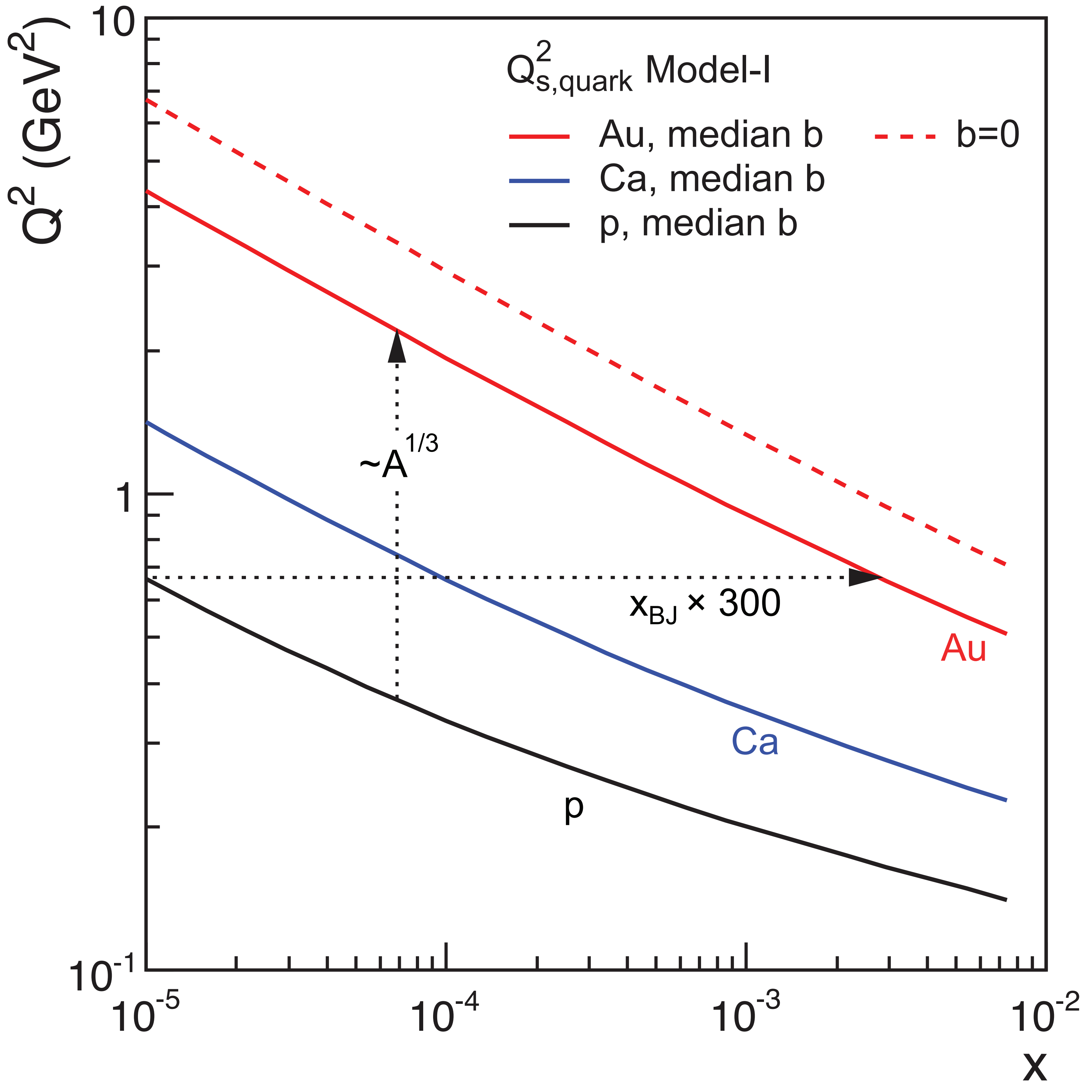
$$Q_s^2 \sim \frac{\alpha_s\, xG(x,Q_s^2)}{\pi R_A^2} \qquad \mathrm{HERA:}\ \ xG \sim \frac{1}{x^{0.3}} \qquad \mathrm{A\ dependence:}\ \ xG_A \sim A$$

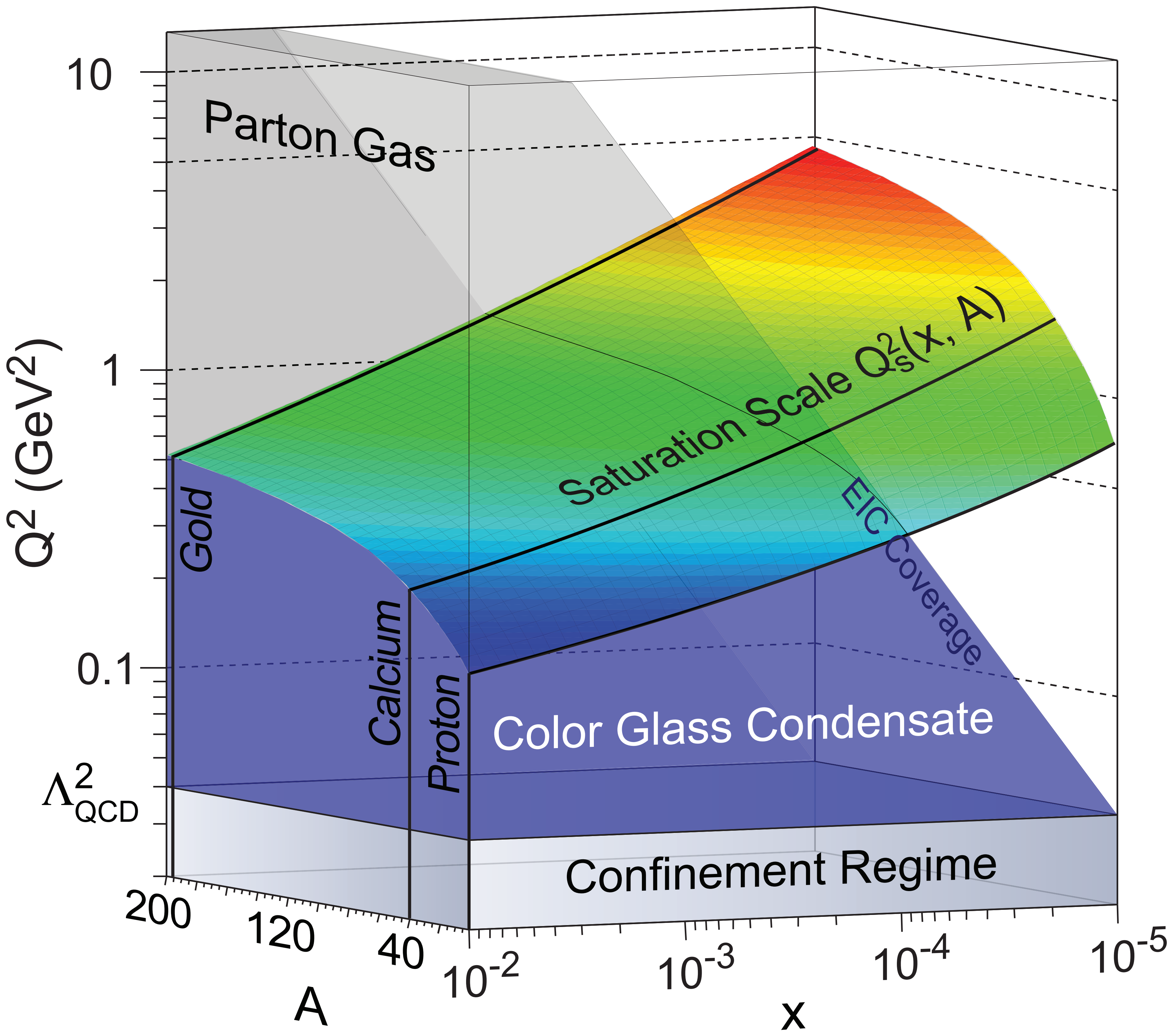
"Expected"
Nuclear Enhancement Factor
(Pocket Formula):

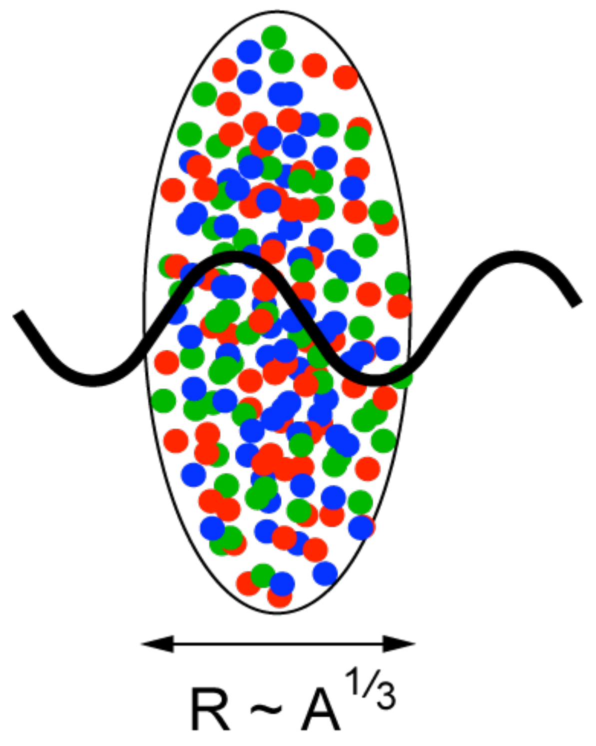
$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$



Enhancement of Saturation Scale







$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A:
saturation regime reached at significantly lower energy in nuclei (and lower cost)

Some Interesting Ideas

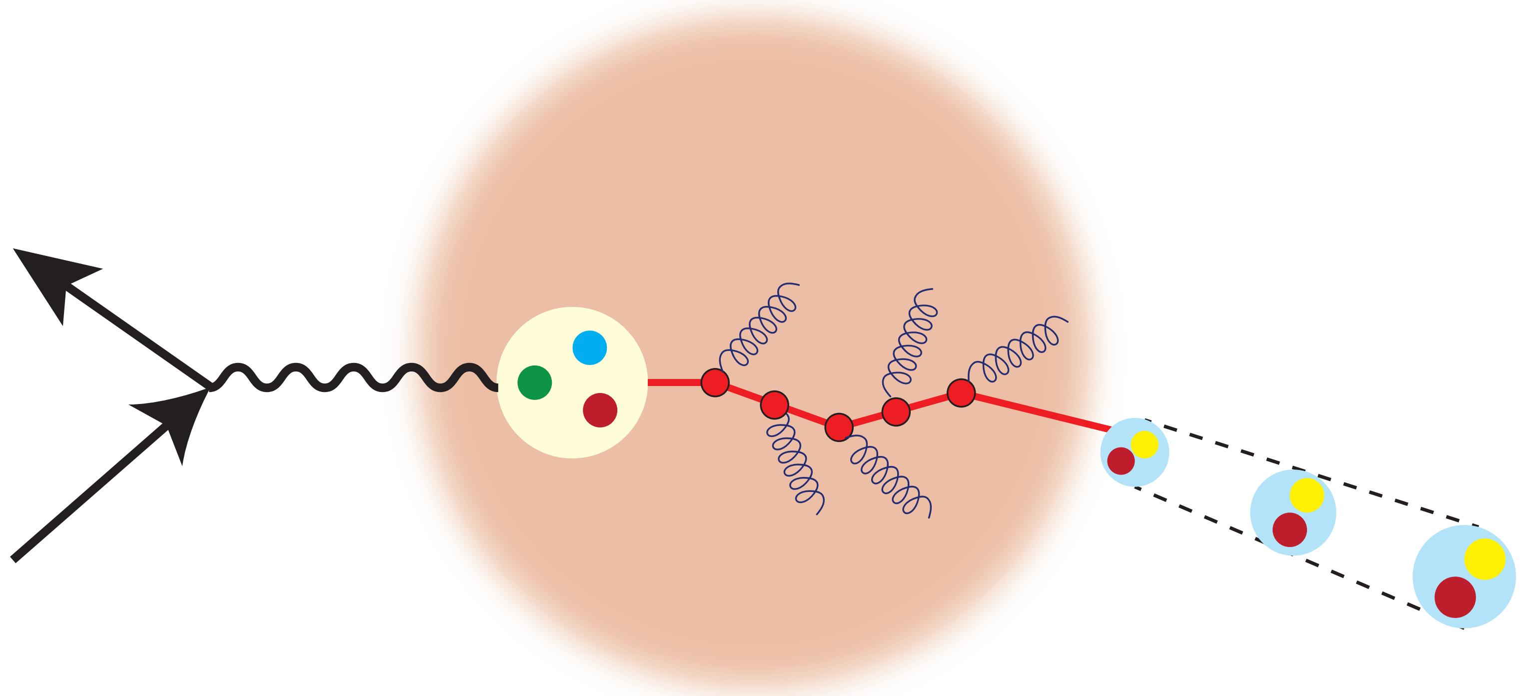
- Conjecture I:
  - at very low-x all hadrons $Q_S(x)$ becomes equal for nucleons, nuclei, mesons, baryons …
  - maybe even for photons (more later)
  - truly **universal** regime
- Conjecture II:
  - as $Q_s(x)$ grows towards small-x, Q_s becomes the largest scale, hence $\alpha_s(Q^2) \rightarrow \alpha_s(Q_s^2)$
  - end of the line for α_s (as long as $Q < Q_s$) ?

Physics at extreme low-x appears to be a wonderland. Experimentally we might not get there in our life time.

Fragmentation

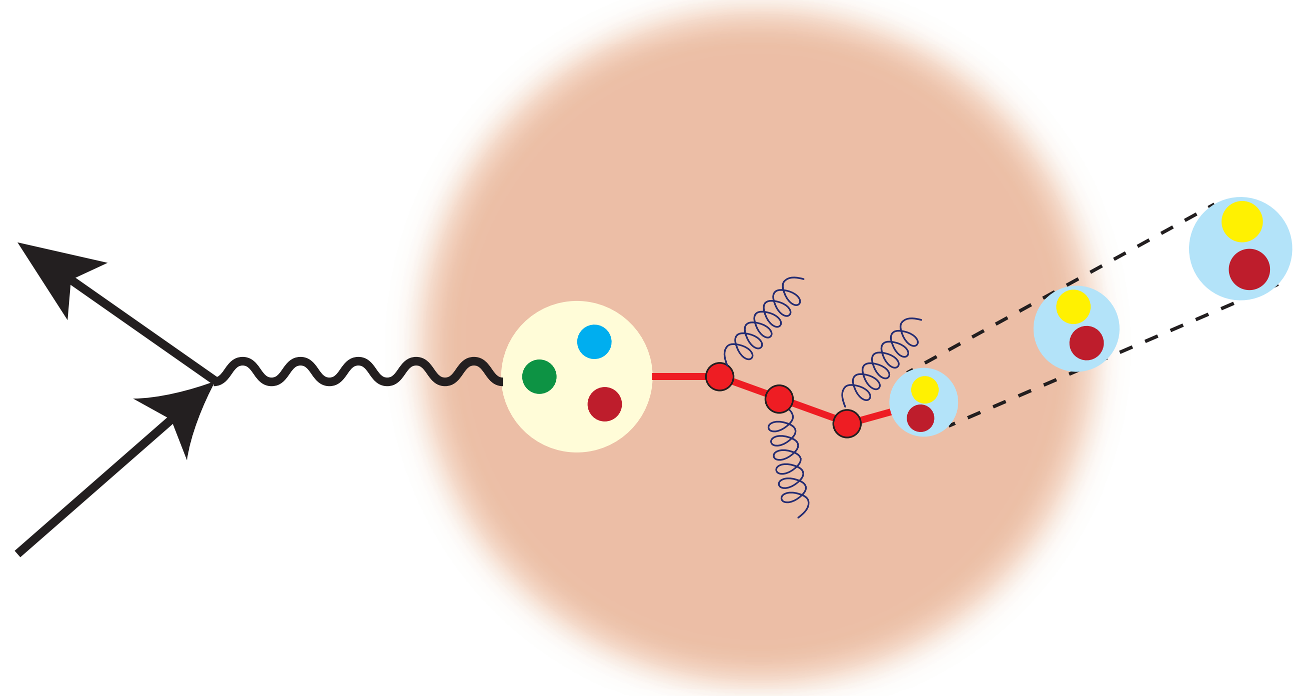
Confinement intimately connected with hadronization

- How do color charges propagate, shower, hadronize ?
  - Process not understood from first principles (QCD)
  - Parametrization: Fragmentation Functions
  - Nuclei can act as femto-detectors of parton showering and hadronization



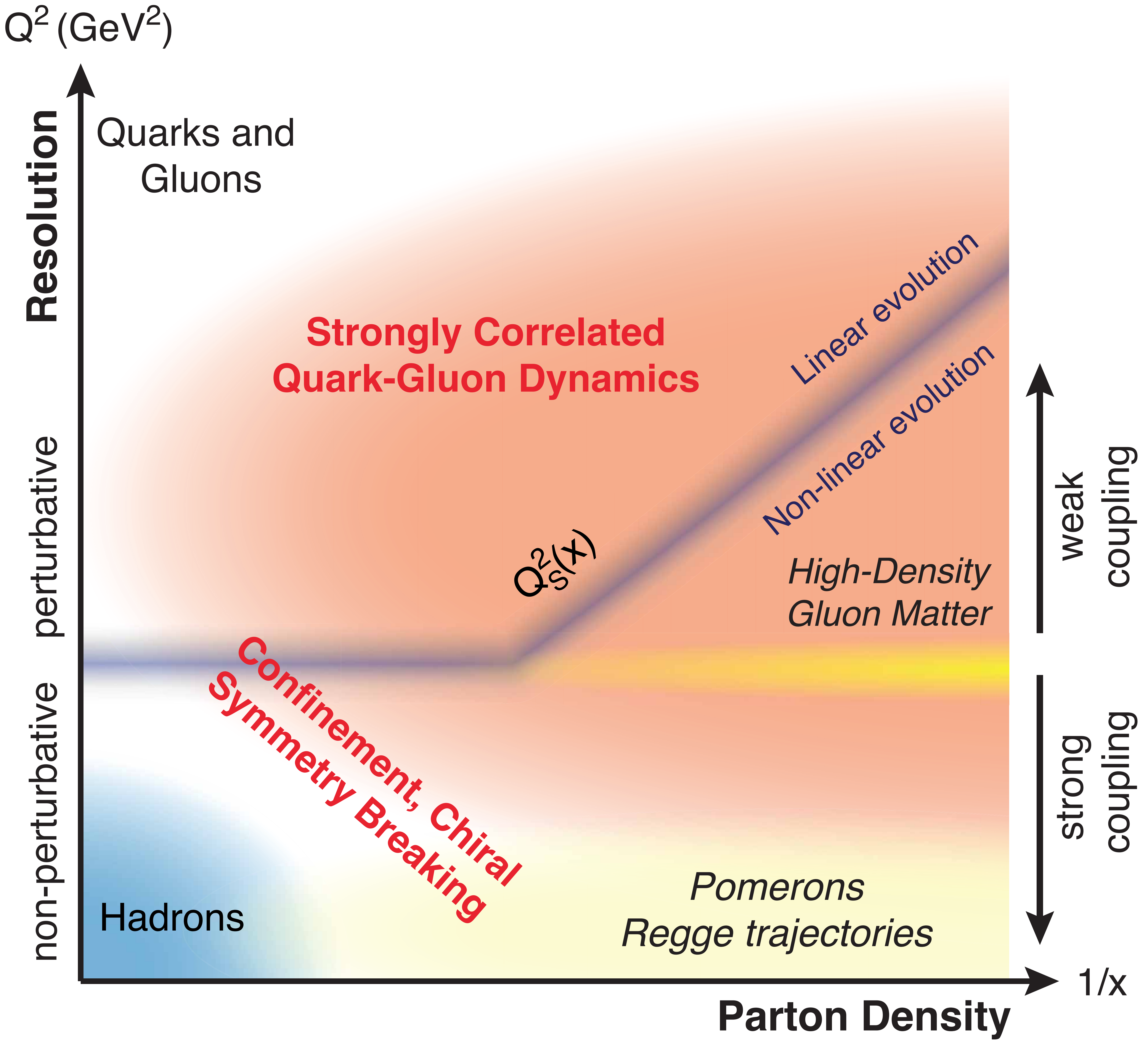
- Color neutralization
- Hadron formation

} dynamic confinement

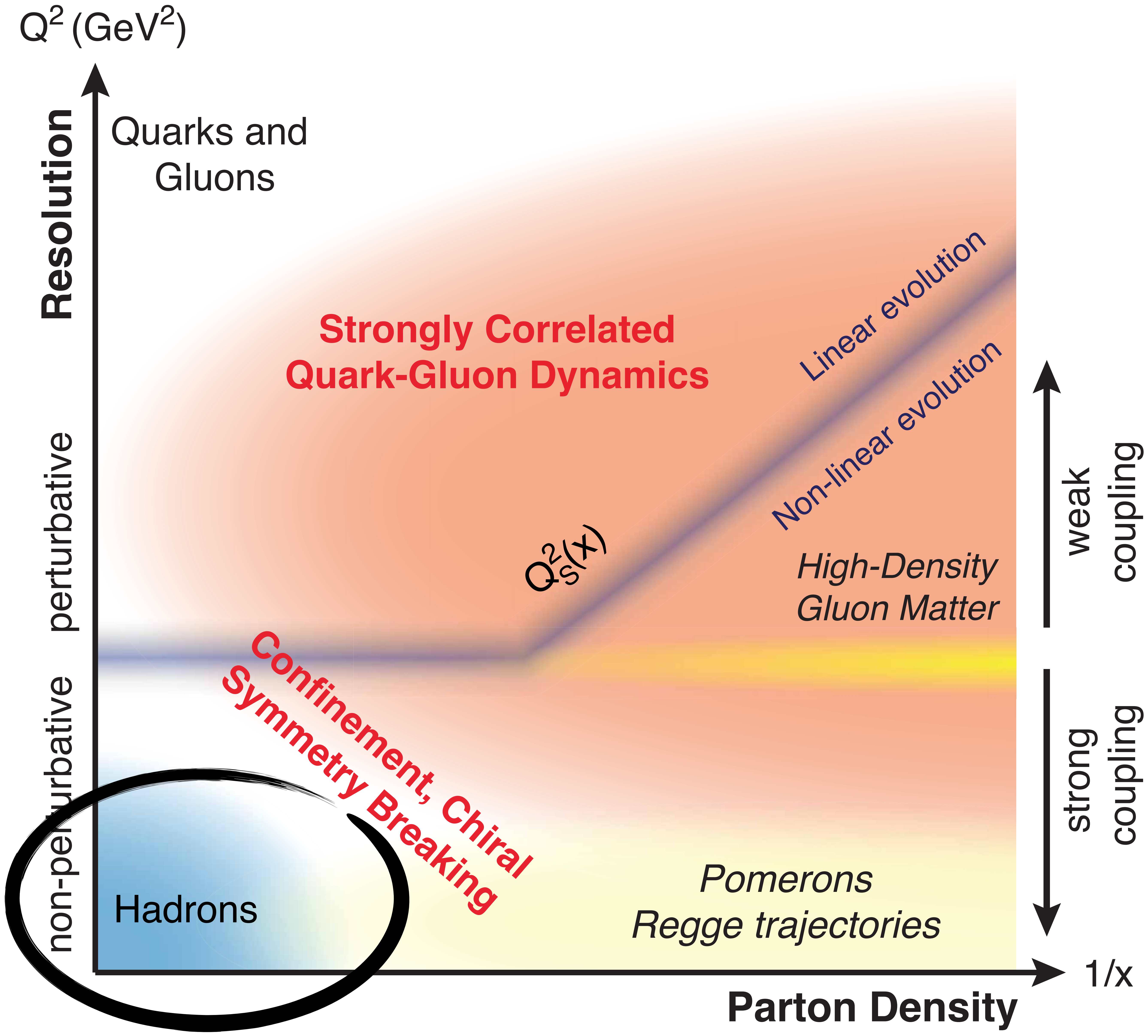


- Nuclei as space-time analyzer allows to dissect process

Faszinating Landscape of QCD

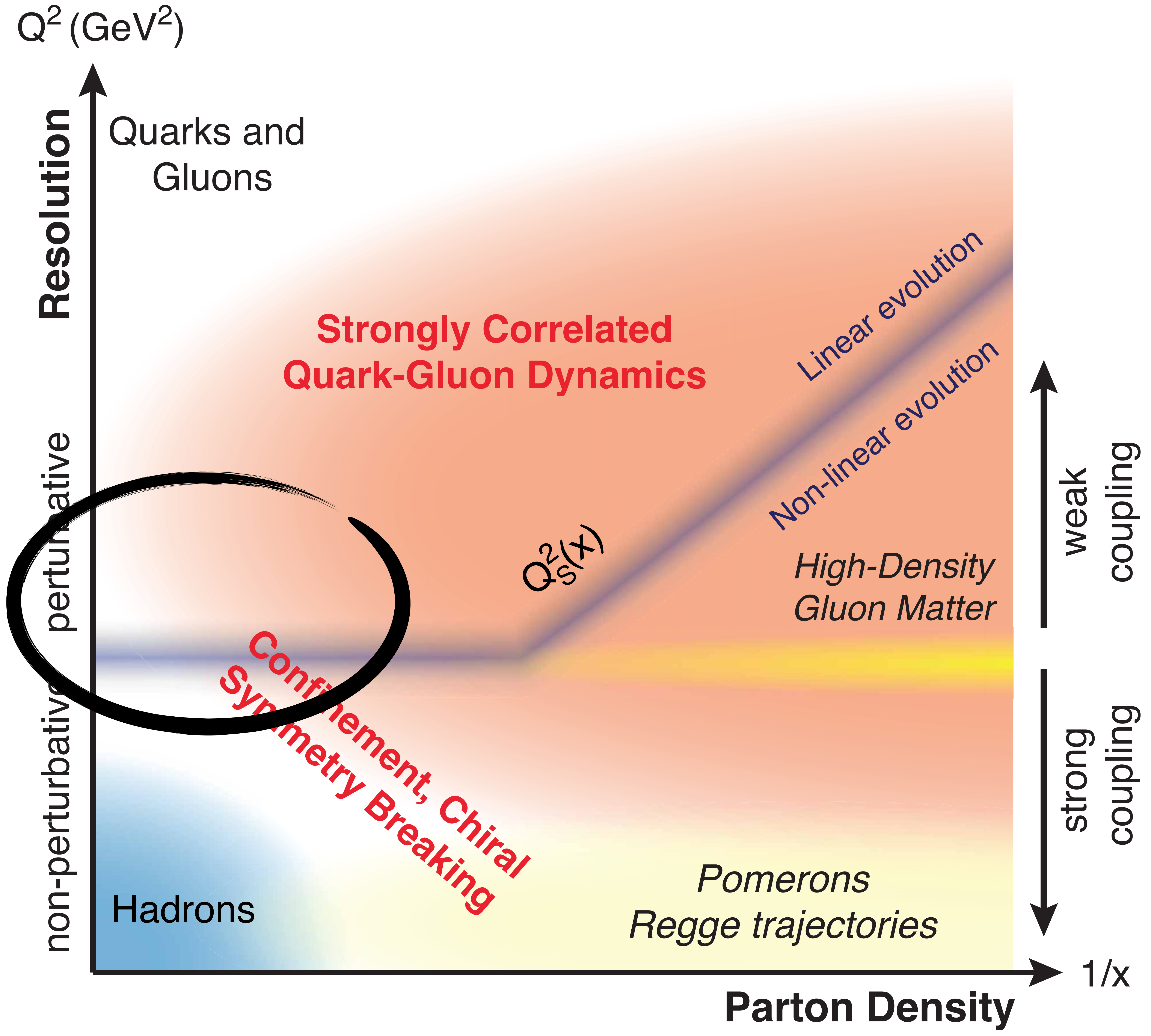


Faszinating Landscape of QCD



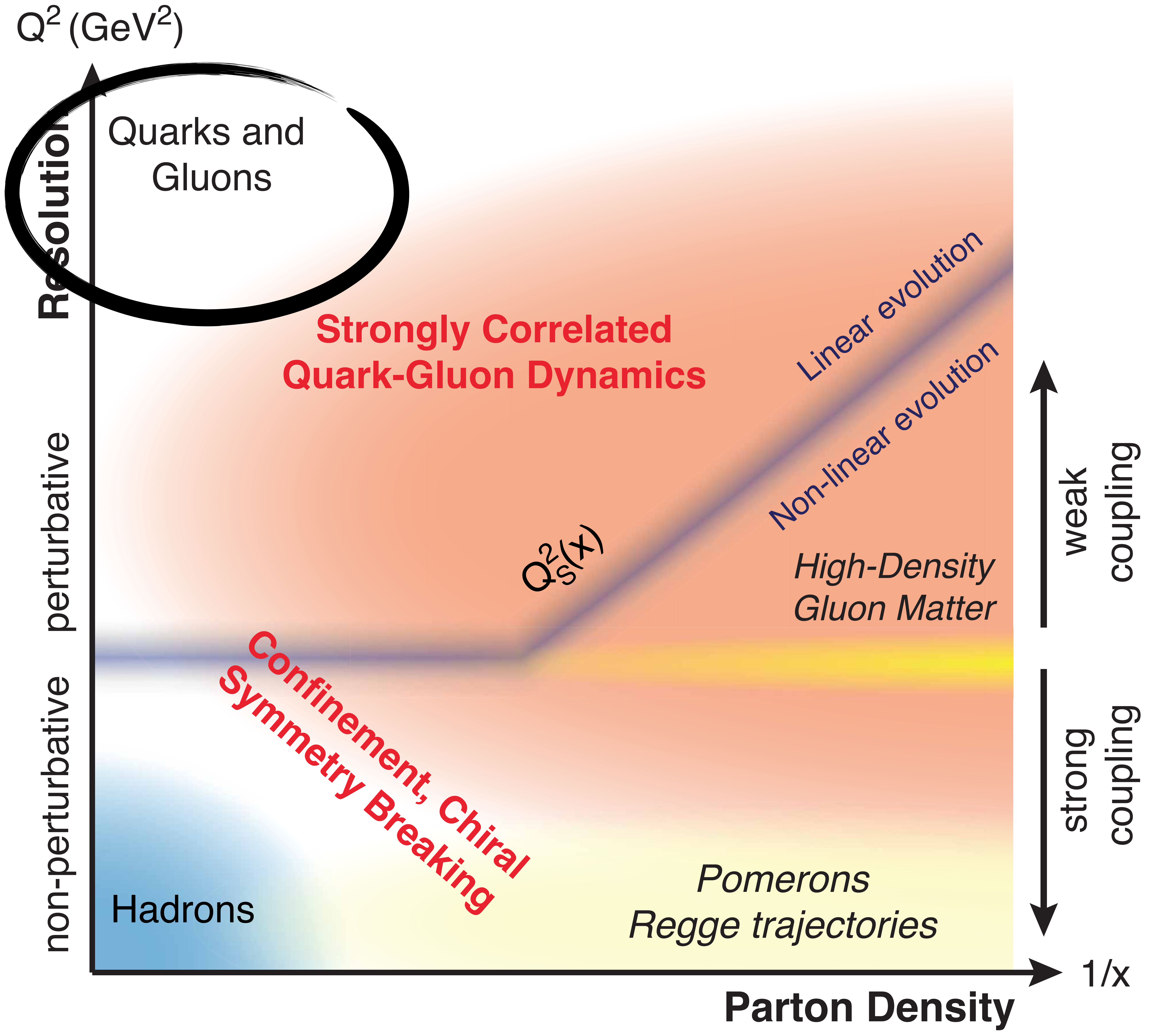
QCD coupling is large, the fields are nonlinear, and the physics is nonperturbative.

Faszinating Landscape of QCD



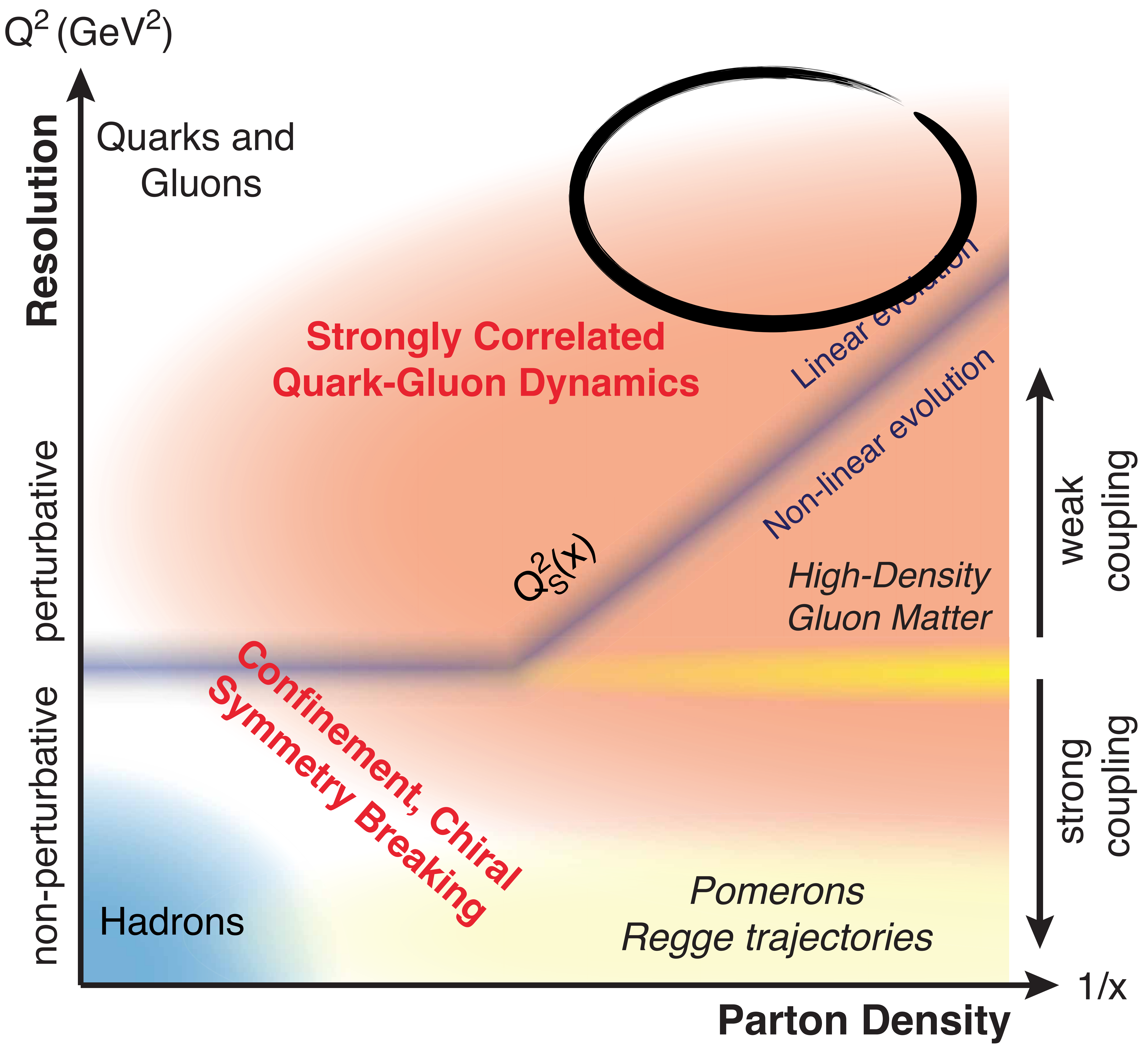
What the degrees of freedom describing this transition region are, is not understood

Faszinating Landscape of QCD



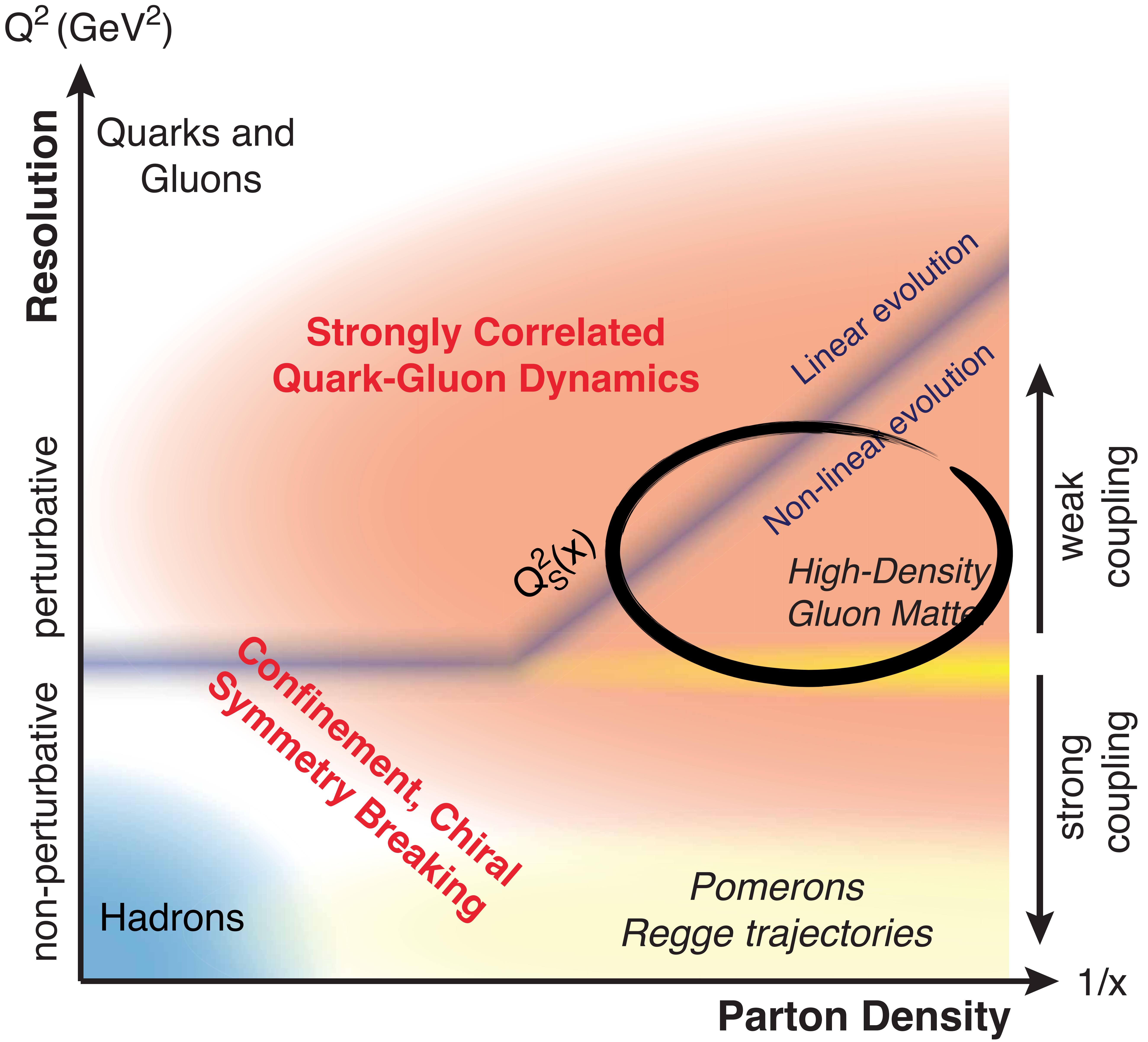
The coupling becomes weak due to asymptotic freedom, and perturbative QCD describes well the interactions of quarks and gluons.

Faszinating Landscape of QCD



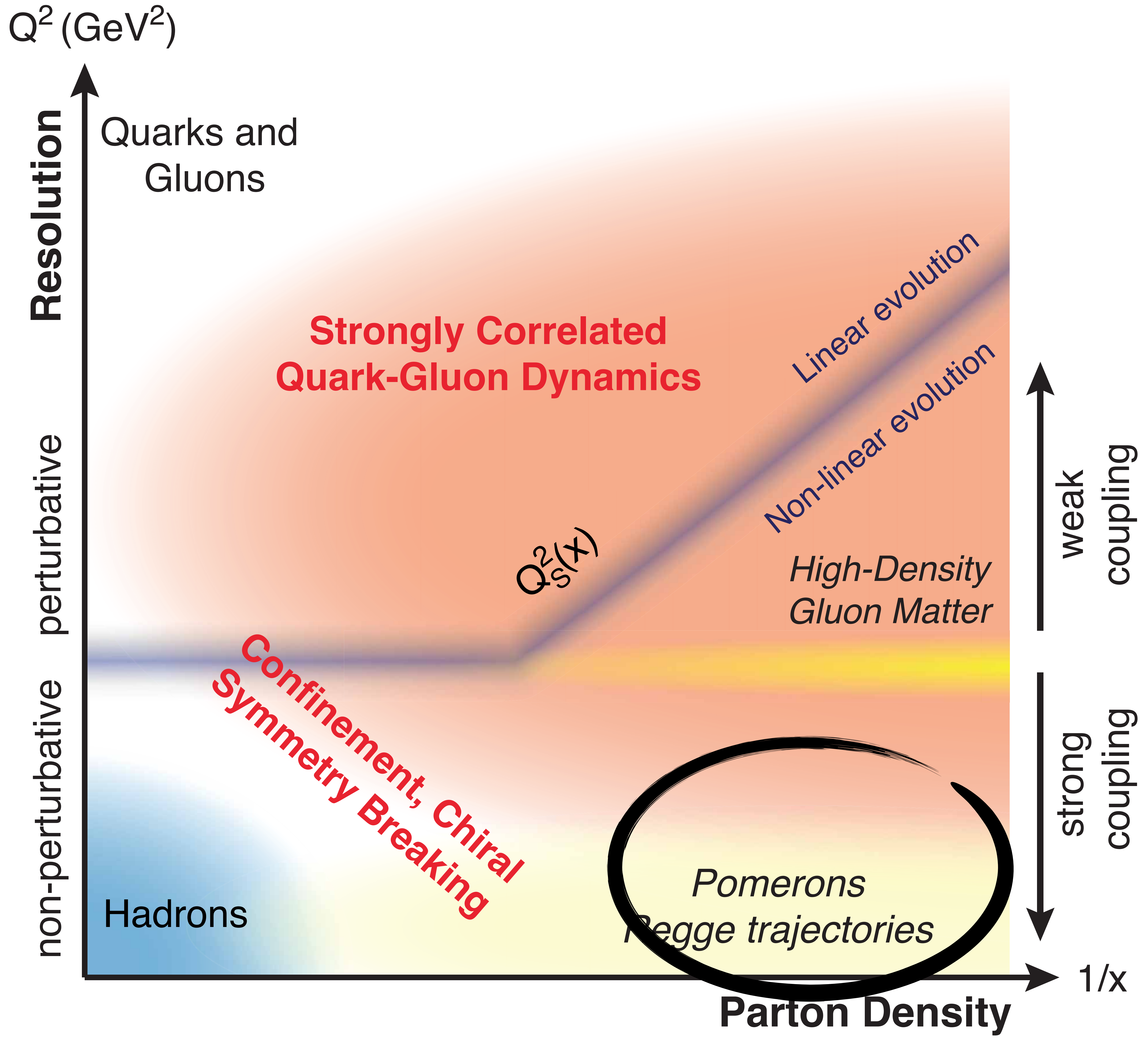
At large Q², as one moves towards higher parton density, many-body correlations between quarks and gluons become increasingly important.

Faszinating Landscape of QCD



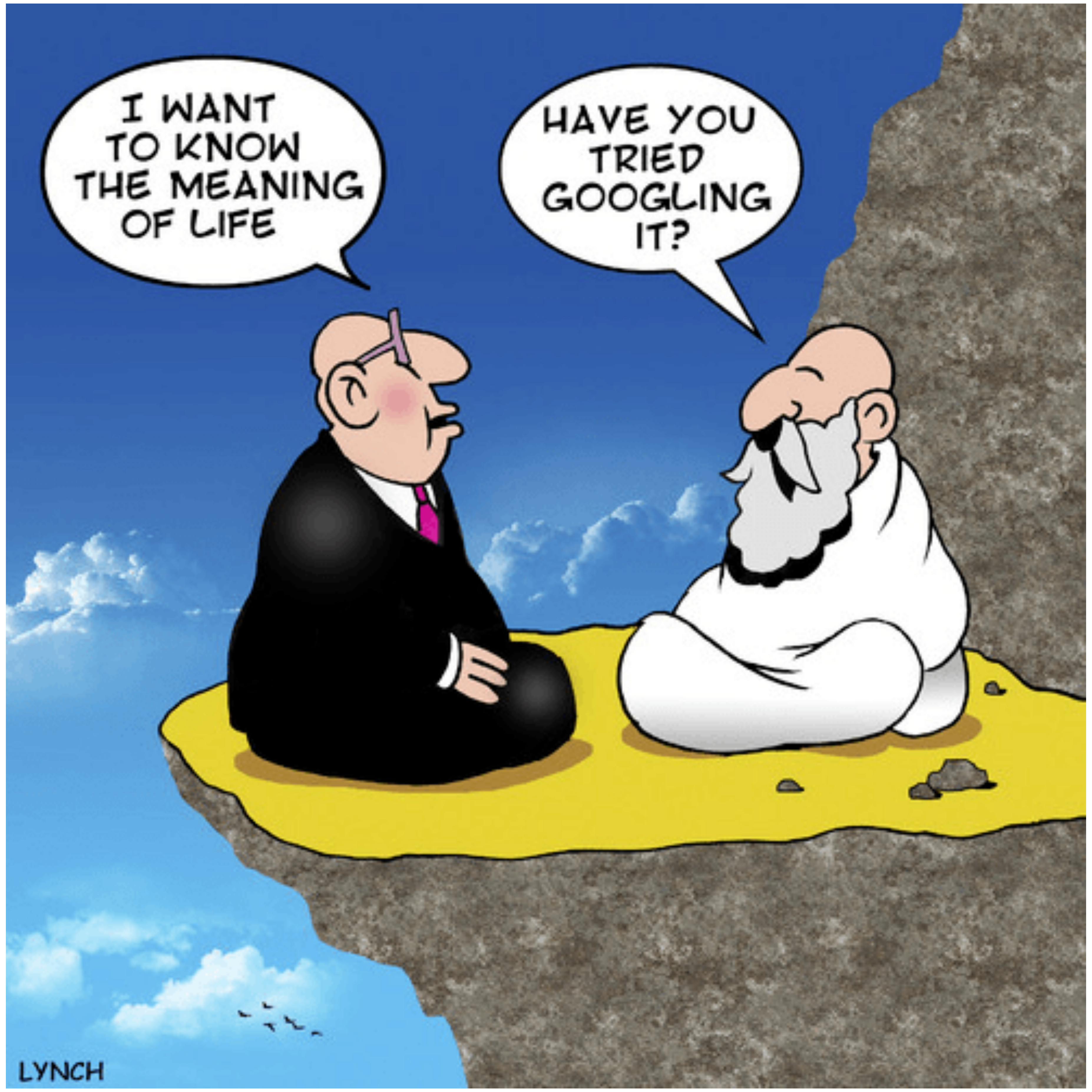
The feature of weak coupling is key because it allows, for the first time, systematic computations of the manybody dynamics of quarks and gluons in an intrinsically nonlinear regime of QCD.

Faszinating Landscape of QCD



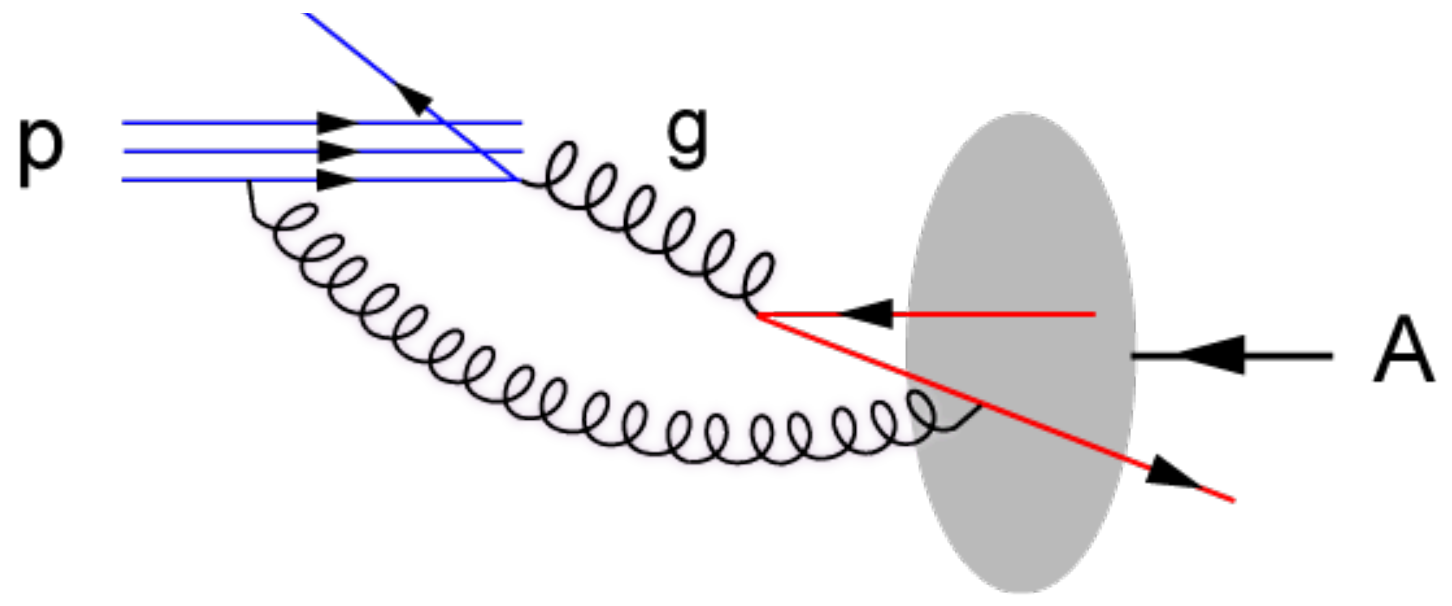
Total cross-sections in high energy scattering are dominated by the physics of small x and low Q^2. The least understood region

4. What Do We Need ?



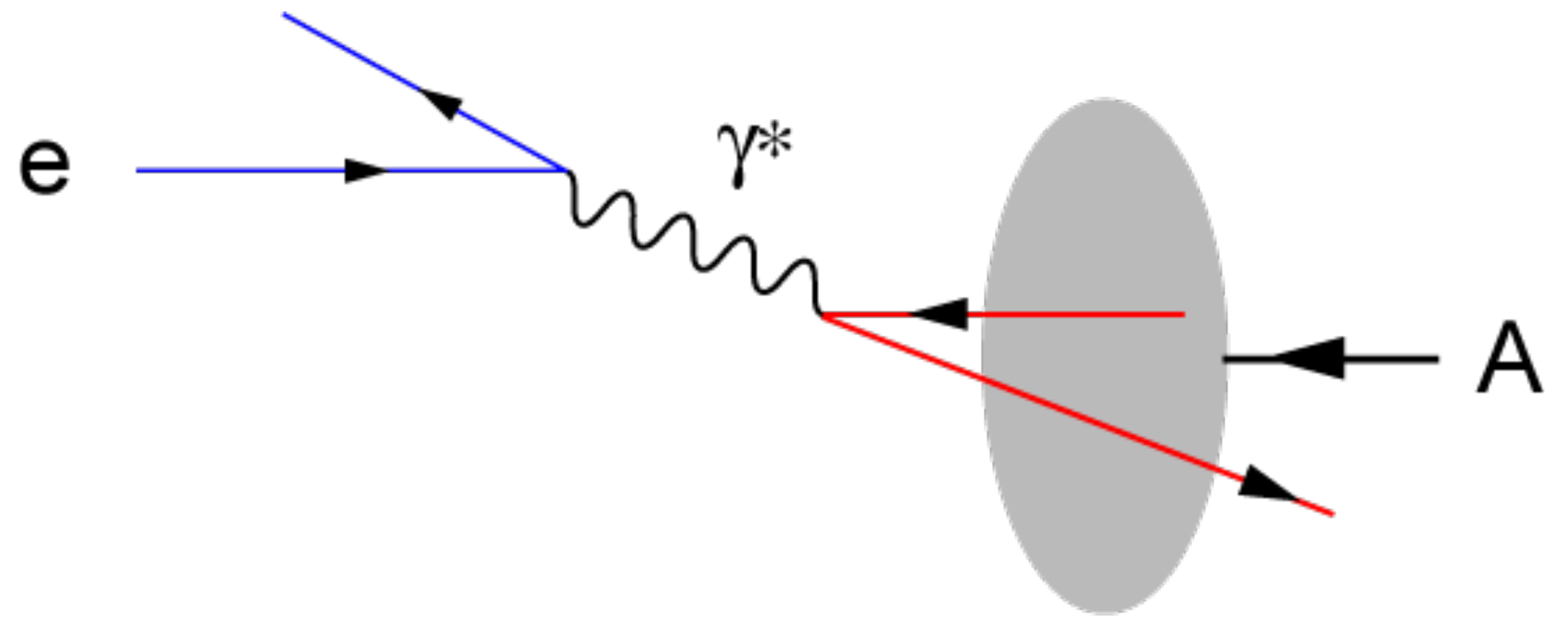
We Need to Collide Something, What?

Hadron-Hadron



- Test QCD
- Probe/Target interaction directly via gluons
- lacks the direct access to x, Q^2

Electron-Hadron (DIS)



- Explore QCD & Hadron Structure
- Indirect access to glue
- High precision & access to partonic kinematics

Both are complementary and provide excellent information on properties of gluons in the nuclear wave functions

Precision measurements ⇒ **DIS** due to unprecedented exact knowledge of QED

OK, e+p

Proton serves as:

- How do quark and gluon dynamics generate the proton spin?
- What is the role of the orbital motion of sea quarks and gluons in building up the nucleon spin?
- How are the sea quarks and gluons distributed in space and transverse momentum inside the nucleon?
- How are these distributions correlated with overall nucleon properties, such as spin direction?

Object of Interest

And e+A

Nucleus serves as:

- What is the fundamental quark-gluon structure of atomic nuclei?

Object of Interest

- Can we experimentally find and explore a novel universal regime of strongly correlated QCD dynamics?
- What is the role of saturated strong gluon fields, and what are the degrees of freedom in this strongly interacting regime?

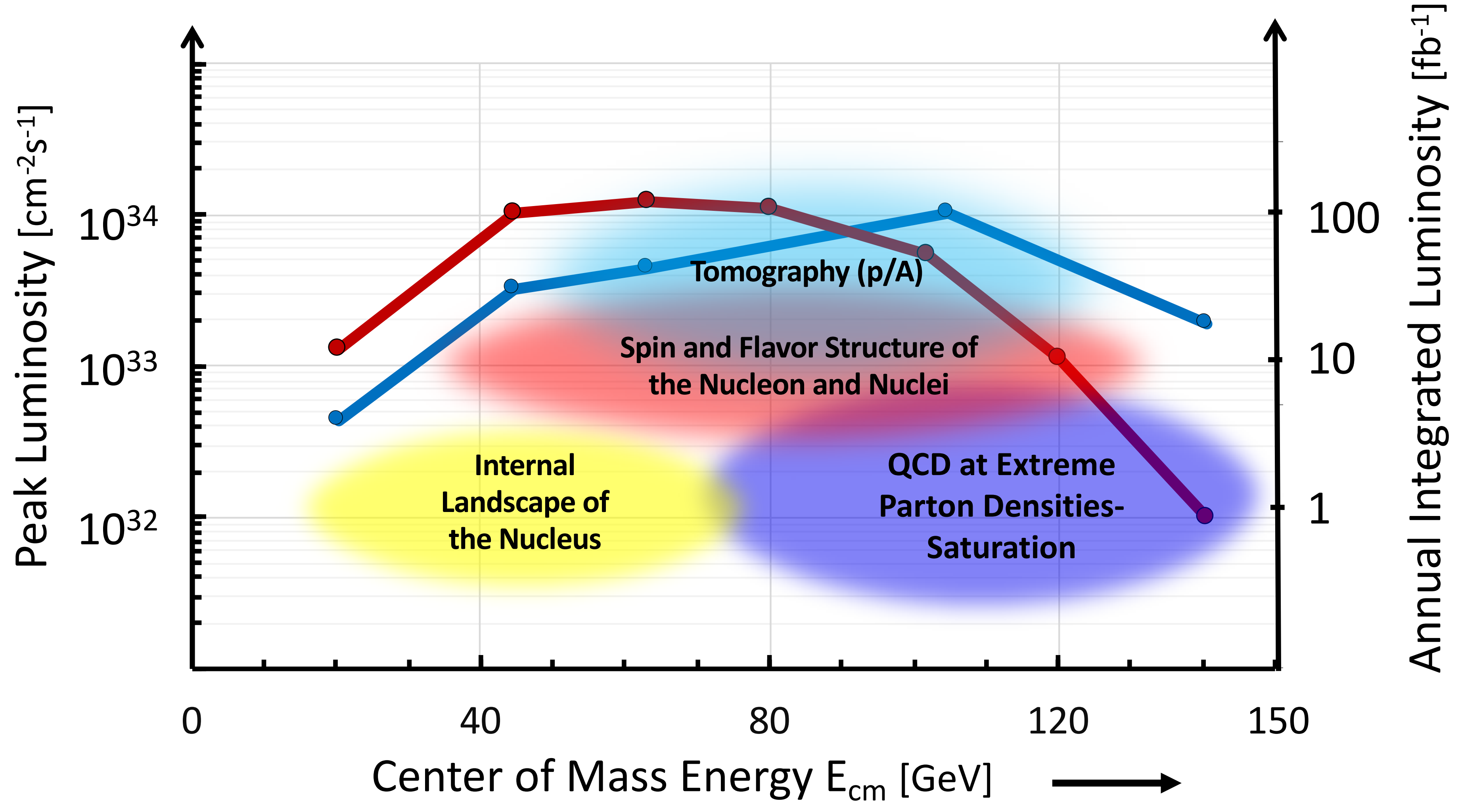
Amplifier

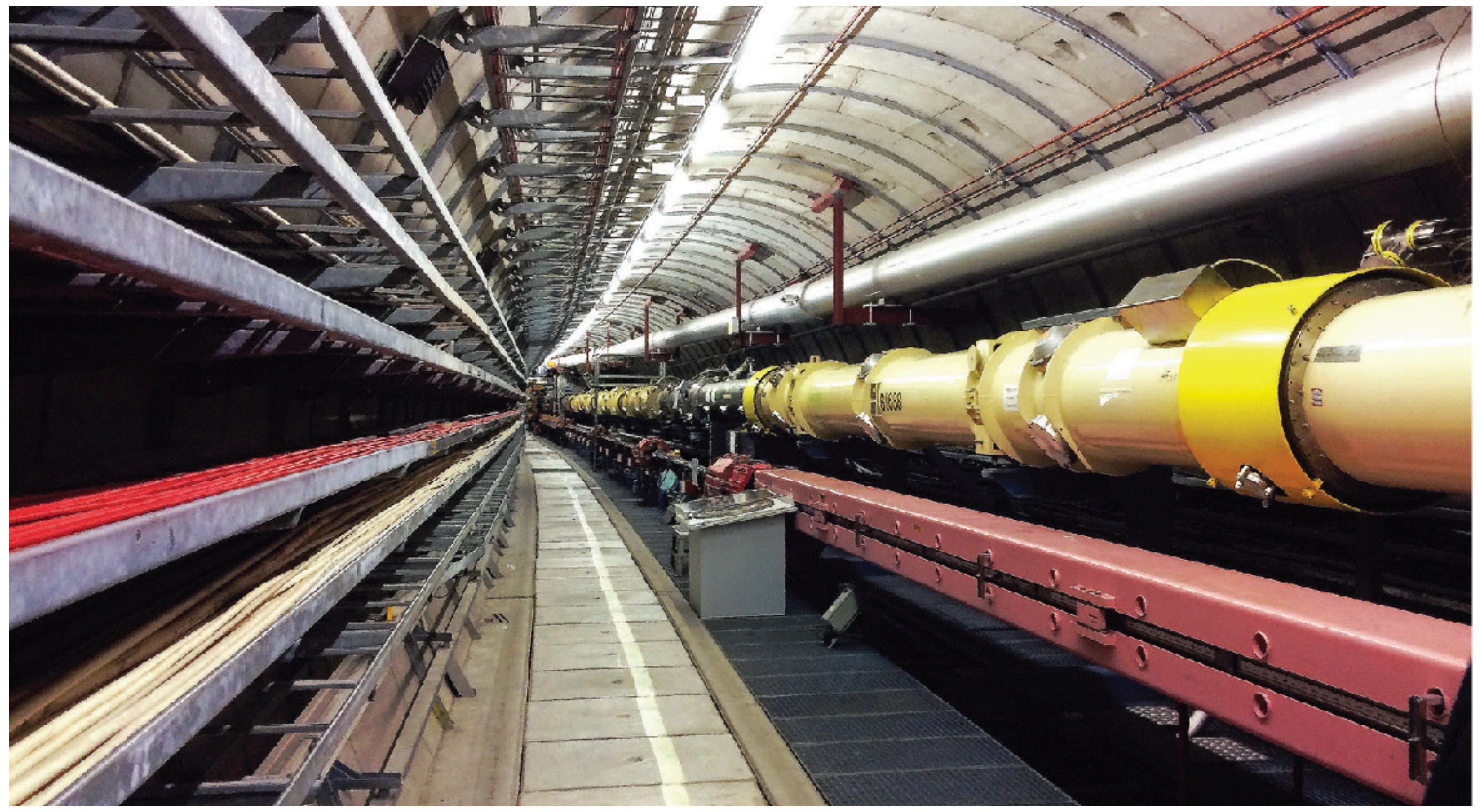
- Can the nuclear color filter provide novel insight into propagation, attenuation and hadronization of colored probes?

Analyzer

What Else?

- Access to gluon dominated region and wide kinematic range in x and Q^2
  - ➡ Large center-of-mass energy range $\sqrt{s}$ = 20 -140000 GeV
- Access to spin structure and 3D spatial and momentum structure
  - ➡ Polarized electron and proton and light nuclear beams ≥ 70% for both
- Accessing the highest gluon densities ($Q_S^2 \sim A^{1/3}$)
  - ➡ Nuclear beams, the heavier the better (up to U)
- Studying observables as a fct. of x, Q^2, A, etc.
  - ➡ High luminosity (100x HERA): $10^{33\text{-}34}$ cm^{-2} s^{-1}





HERA@DESY

Siberian Snakes, RHIC

Reality Check

Designing a dream machine is easy but

- It has to be fundable
- The technology has to be available
- Path of failed efforts is long: Isabelle, SSC, …

Find the parameters that do the job and that actually can be realized!

EIC:

- Highly polarized (70%) e- and p beams
- Ion beams from D to U
- Variable center-of-mass energies from $\sqrt{s}$=20-140 GeV
- High collision luminosity $10^{33\text{-}34}$ $cm^{-2}s^{-1}$ (HERA ~ 10^{31})
- Possibilities of having more than one interaction region

Does Something Already Exist?

Past / Future

	HERA@DESY	LHeC@CERN	HIAF@CAS	ENC@GSI	EIC
$\sqrt{s}$ (GeV)	320	800-1300	12-65	14	32-140
Proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-4}	5×10^{-3}	5×10^{-5}
Ions	p	p … Pb	p … U	p … Ca	p … U
L ($cm^{-2}s^{-1}$)	2×10^{31}	$\sim10^{34}$	$\sim10^{32-35}$	$\sim10^{32}$	$\sim10^{33-34}$
IRs	2	1	1	1	2+
Year	1992-2007	post ALICE	> 2020?	Fair Upgrade	post RHIC

High-Energy Physics / Nuclear Physics

Only one in the making

- World-wide interest in EIC
- All future collider ideas include e+A in their planning

Postscriptum: What are Leptoquarks

Leptoquarks are hypothetical particles that carry both lepton (L) and baryon number (B). Their other quantum numbers, like spin, (fractional) electric charge and weak isospin vary among models. Leptoquarks are encountered in various extensions of the Standard Model, such as technicolor theories, theories of quark–lepton unification (e.g., Pati–Salam model), or GUTs based on SU(5), SO(10), E6, etc. Leptoquarks are currently searched for in experiments ATLAS and CMS at the Large Hadron Collider in CERN.

Table 94.1: Possible leptoquarks and their quantum numbers.

Spin	$3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
0	-2	$\bar{3}$	1	1/3	$\bar{q}_L^c \ell_L$ or $\bar{u}_R^c e_R$
0	-2	$\bar{3}$	1	4/3	$\bar{d}_R^c e_R$
0	-2	$\bar{3}$	3	1/3	$\bar{q}_L^c \ell_L$
1	-2	$\bar{3}$	2	5/6	$\bar{q}_L^c \gamma^\mu e_R$ or $\bar{d}_R^c \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	$-1/6$	$\bar{u}_R^c \gamma^\mu \ell_L$
0	0	3	2	7/6	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	1/6	$\bar{d}_R \ell_L$
1	0	3	1	2/3	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	5/3	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	2/3	$\bar{q}_L \gamma^\mu \ell_L$

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HERA DATA AND LEPTOQUARKS IN SUPERSYMMETRY

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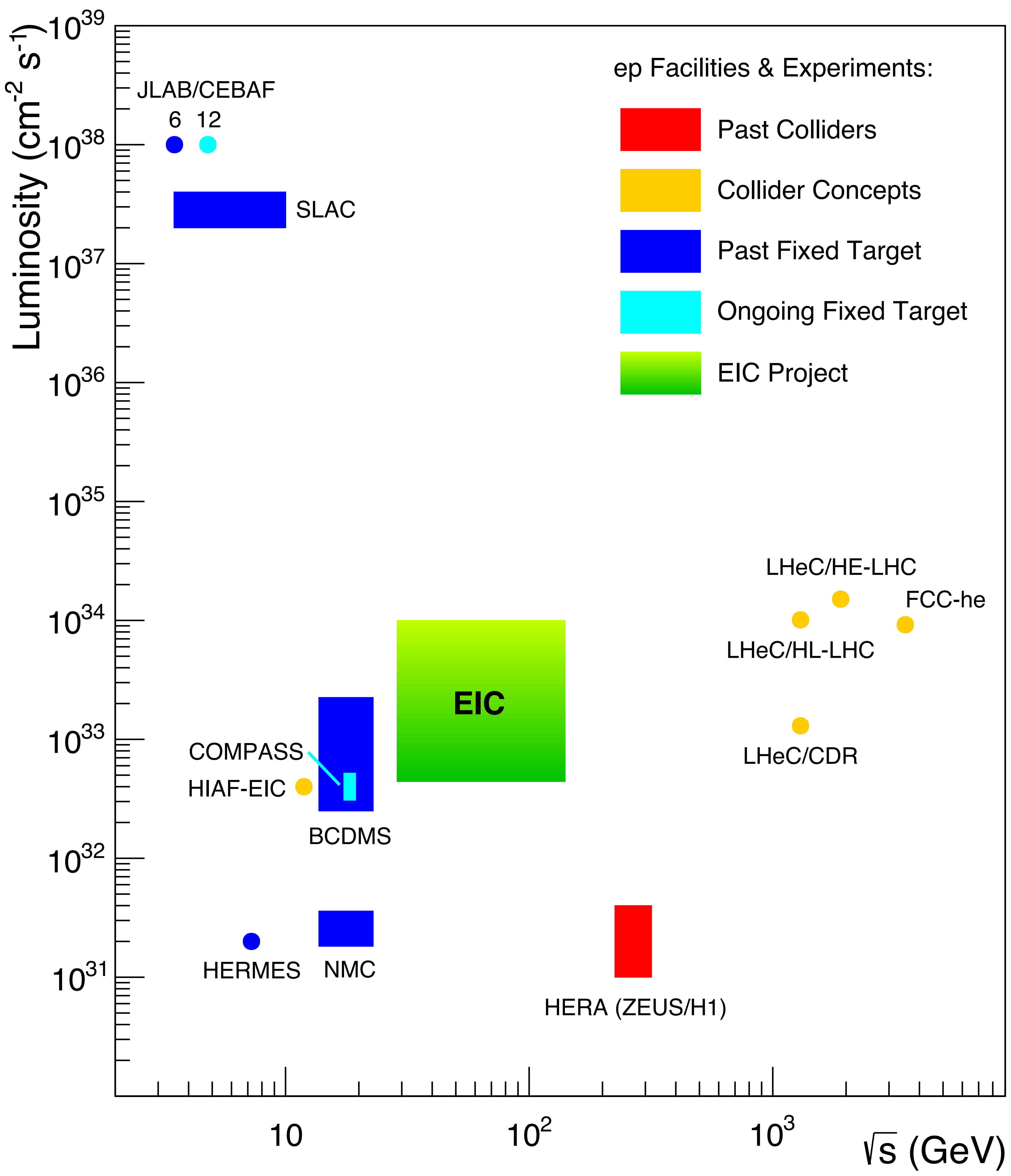
I present a concise review of the possible evidence for new physics at HERA and of the recent work towards a theoretical interpretation of the signal. It is not clear yet if the excess observed at large Q^2 is a resonance or a continuum (this tells much about the quality of the signal). I discuss both possibilities. For the continuum case one considers either modifications of the quark structure functions or contact terms. In the case of a resonance, a leptoquark, the most attractive possibility that is being studied is in terms of s-quarks with R-parity violation. In writing this script I updated the available information to include the new data and the literature presented up to August 1, 1997.

Landscape of DIS: The Uniqueness of EIC



- EIC cannot compete with e+p at HERA ($\sqrt{s}$ = 318 GeV)
- EIC's strength is polarized e↑+p↑ and e+A collisions
- Here the kinematic reach extends substantially compared to past (fixed target) coverage
  - Q^2×20, x/20 for e+A
  - Q^2×20, x/100 for polarized e↑+p↑

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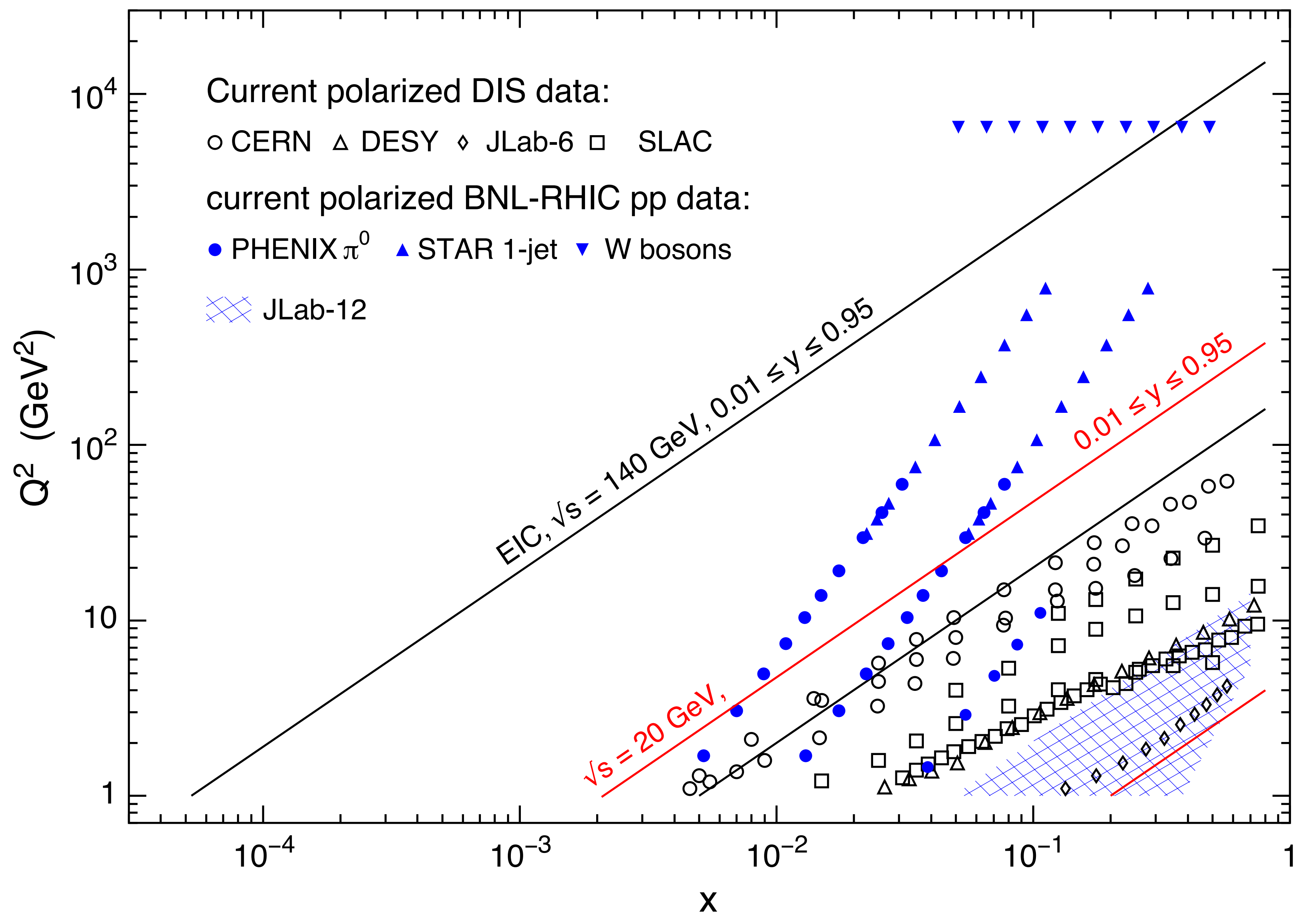

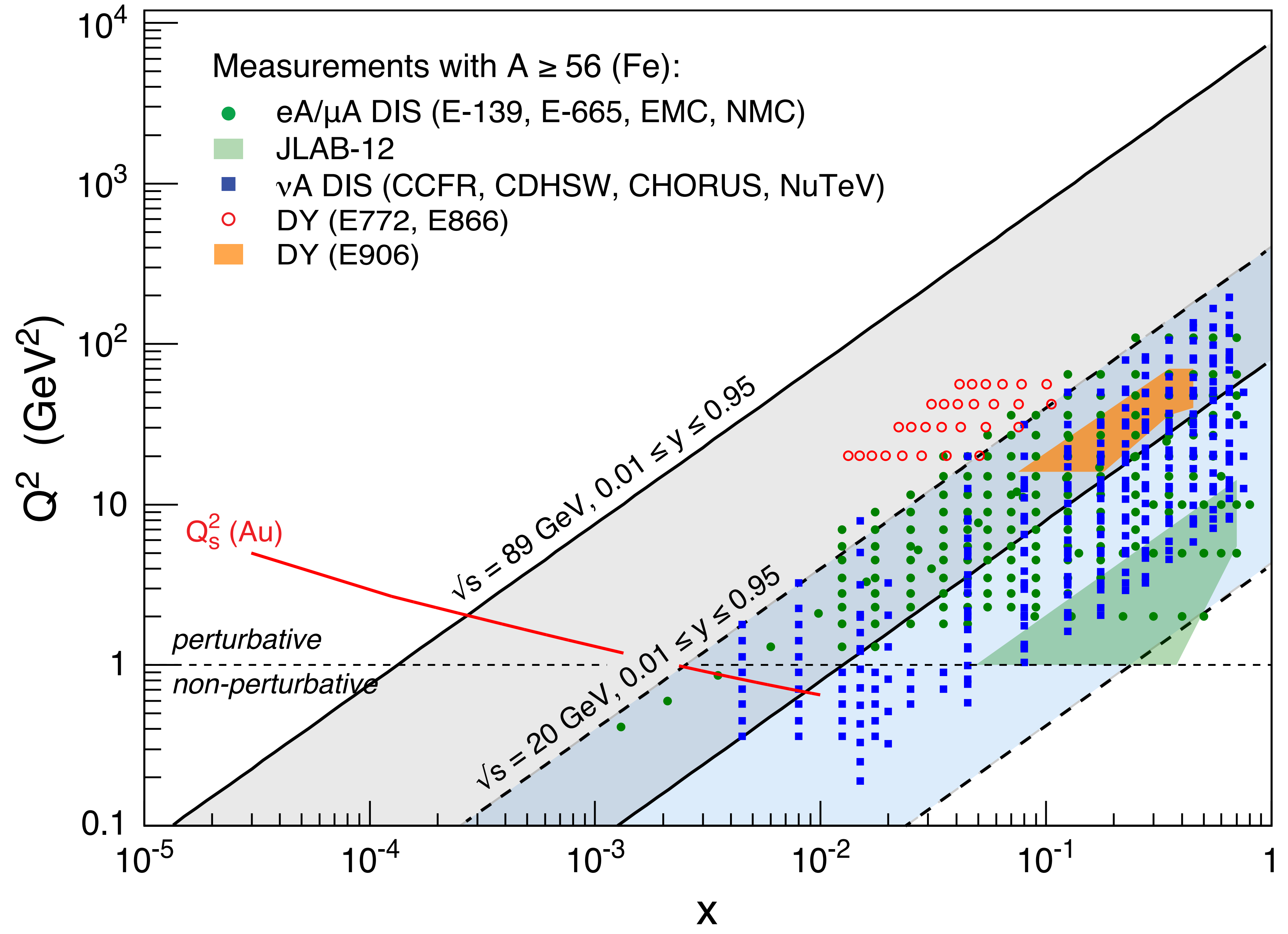

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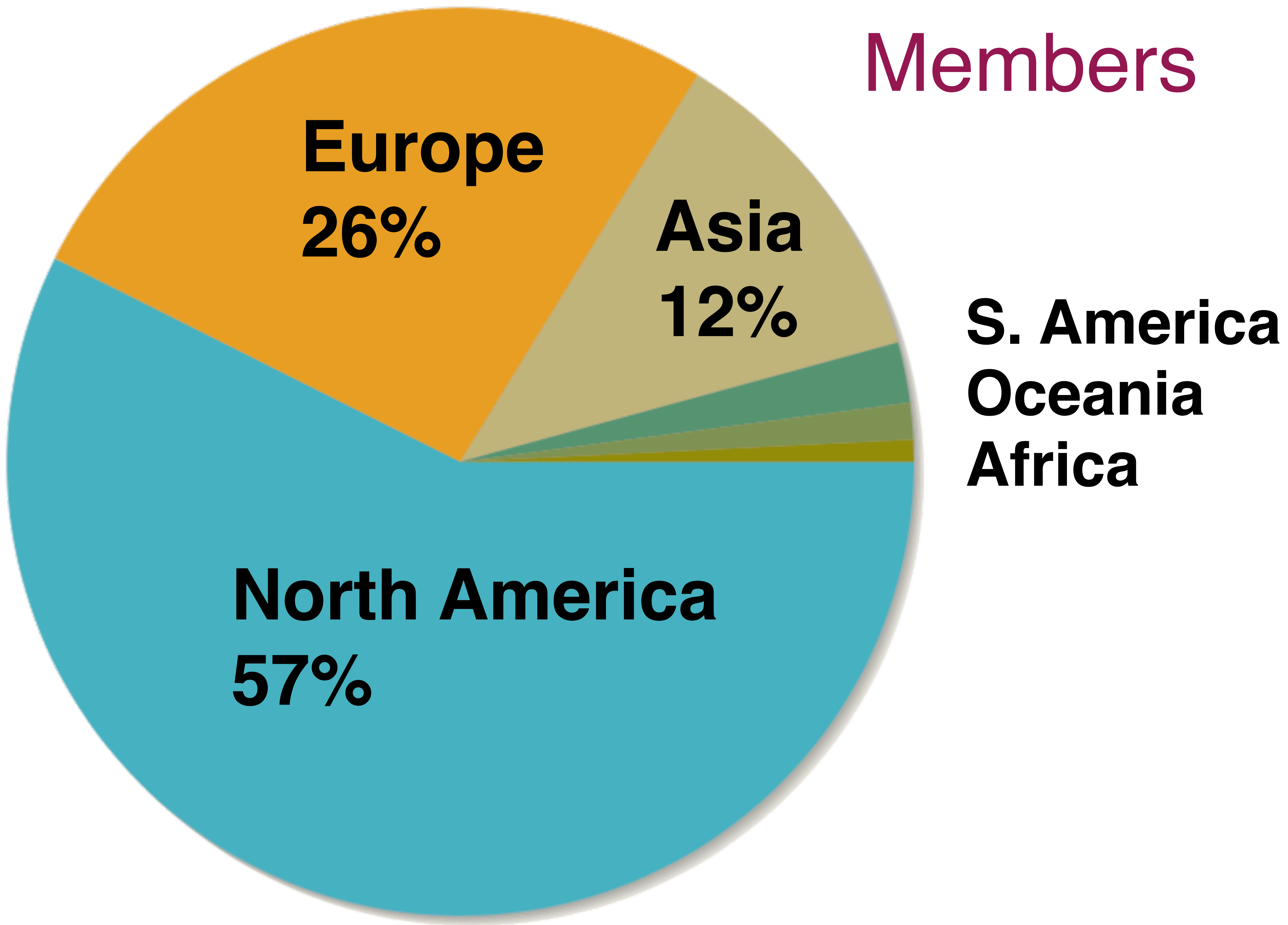
The EIC Community

The EIC User Group: http://eicug.org

- Formation of a formal EIC User Group in 2014/2015
- 1531 members, 295 institutions, 40 countries
- EIC Science Centers at JLab (EIC^2) and BNL/Stony Brook University (CFNS)



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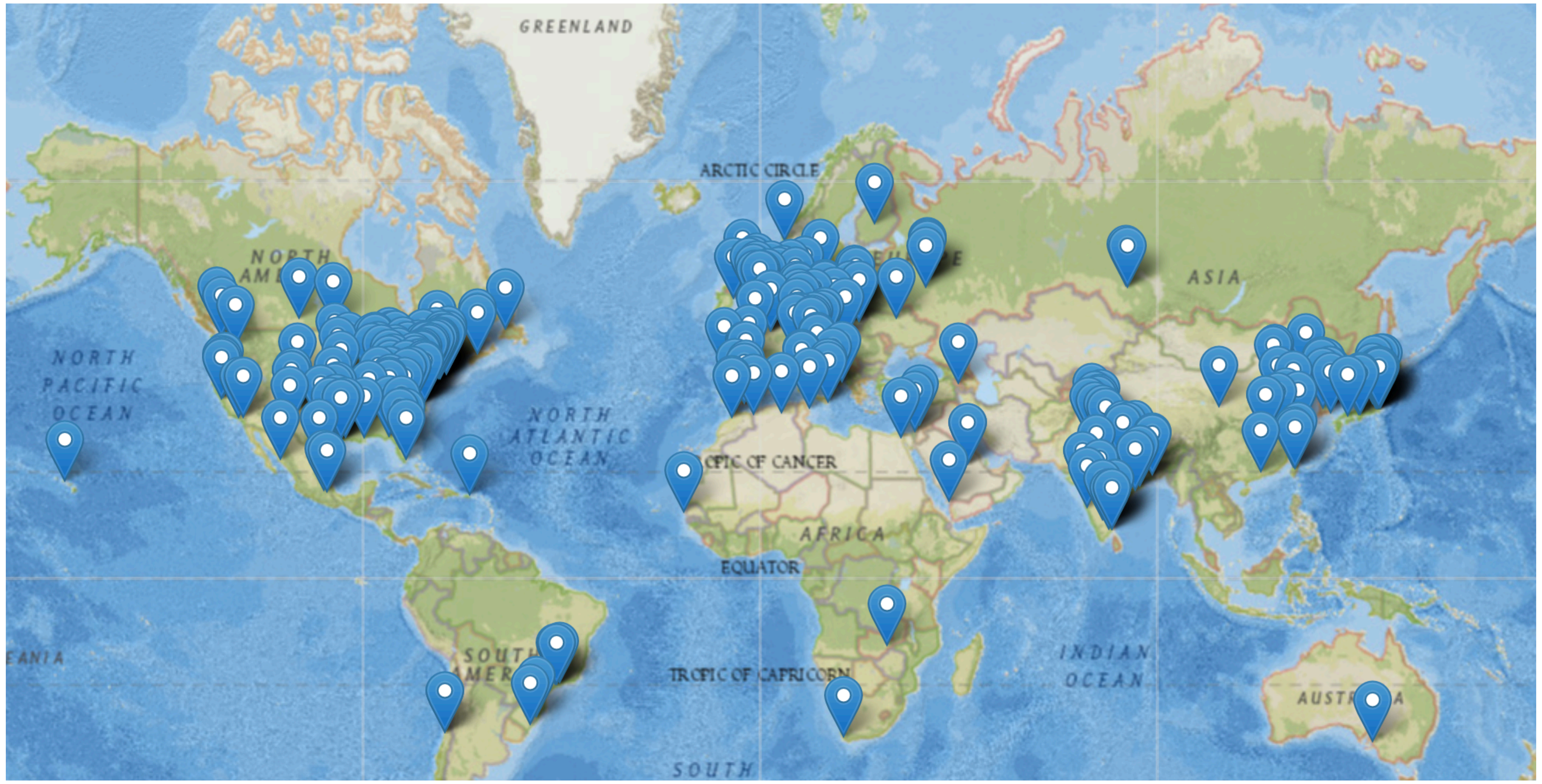

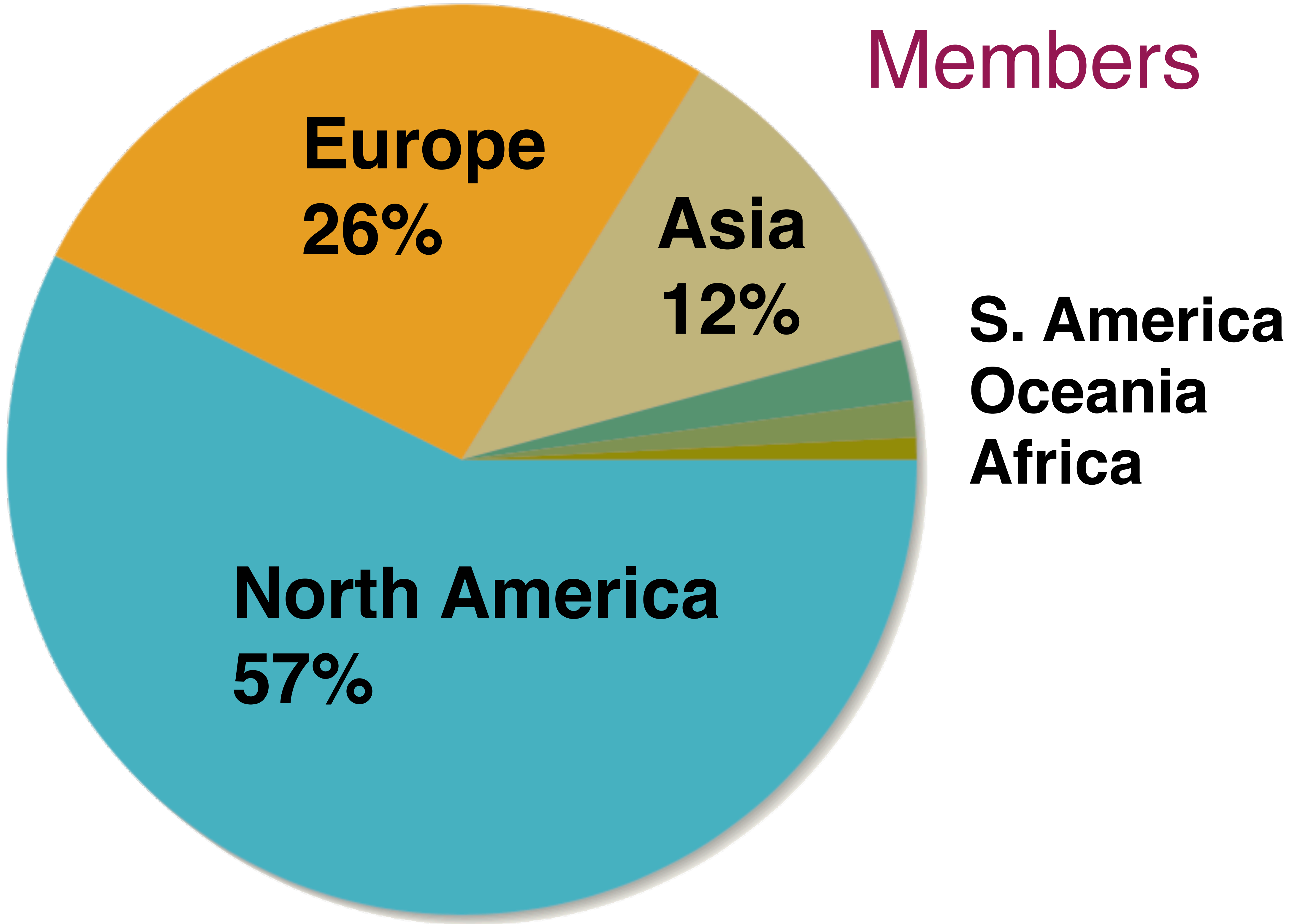

Interesting Comparison:
~25% US participants in LHC collaborations

Money - Lots of

Estimated Cost: \$2-2.8B

- Main funding agent and owner of the EIC: DOE
- Many contributions (in-kind) from around the world
- International effort

How it Works

- DOE’s Order 413.3B outlines a series of staged project approvals, referred to as a “Critical Decision (CD)”
  - CD-0 – Approve Mission Need
  - CD-1 – Approve Alternative Selection and Cost Range
  - CD-2 – Approve Performance Baseline
  - CD-3 – Approve Start of Construction
  - CD-4 – Approve Start of Operations or Project Completion
  - Operation == Physics

The Path to Physics is plastered with reviews and reports